nature climate change

ARTICLES

PUBLISHED ONLINE: 29 MARCH 2011 | DOI: 10.1038/NCLIMATE1066

Climate, health, agricultural and economic impacts of tighter vehicle-emission standards

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Non-CO_2 air pollutants from motor vehicles have traditionally been controlled to protect air quality and health, but also affect climate. We use global composition–climate modelling to examine the integrated impacts of adopting stringent European on-road vehicle-emission standards for these pollutants in 2015 in many developing countries. Relative to no extra controls, the tight standards lead to annual benefits in 2030 and beyond of 120,000–280,000 avoided premature air pollution-related deaths, 6.1–19.7 million metric tons of avoided ozone-related yield losses of major food crops, $US0.6–2.4 trillion avoided health damage and $US1.1–4.3 billion avoided agricultural damage, and mitigation of 0.20 (+0.14/−0.17) °C of Northern Hemisphere extratropical warming during 2040–2070. Tighter vehicle-emission standards are thus extremely likely to mitigate short-term climate change in most cases, in addition to providing large improvements in human health and food security. These standards will not reduce CO_2 emissions, however, which is required to mitigate long-term climate change.

Fossil-fuel combustion is a major source of pollutants that both alter climate and degrade air quality[1,2]. A large and rapidly growing source of emissions is from on-road motor vehicles: cars, trucks and motorcycles[1,3]. Although much is known about how vehicle emissions affect air quality, there have been fewer studies of how vehicle emissions affect climate. Climate projections typically include vehicle emissions in scenarios with simultaneous changes in emissions from multiple sources. Several recent studies have specifically isolated the climate forcing from transportation, looking at current emissions[4–8]. Emission controls affect individual pollutants differently, however, hence their effects will not simply be proportional to the impact of current emissions. Additionally, vehicle emissions vary regionally, depending on vehicle ownership and usage rates, vehicle types, and emission and fuel standards, as do control options, in part owing to institutional capacity differences. We, therefore, examine the effects of plausible tight standards region by region. We also analyse the effects of emission controls on diesel and petrol vehicles separately as these two technologies emit different mixes of pollutants. We make an integrated analysis of both the impacts on climate and the effects on human health and crop yields of tighter vehicle-emission standards.

Baseline and tight-standard scenarios

Emission inventories were created for a baseline scenario that assumes full implementation of currently proposed or adopted standards (with no extra standards added in the future) and an aggressive tight-standard scenario. In the latter, existing European emission standards, which are more stringent that those currently planned in developing nations, are imposed in 2015 along with the attendant fuel standards. Emission scenarios were developed for the years 2000–2050 in five-year increments for nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds, sulphur dioxide (SO_2), black carbon (the strongly absorbing fraction of particulate carbon emissions), organic carbon, methane, nitrous oxide and hydrofluorocarbons. Emissions of each species were segregated by vehicle type (except for SO_2, which was separated only into diesel and petrol). No uncertainties in emissions are included.

The tighter standards vary regionally on the basis of expert judgment of local financial, technical and institutional capacity (Table 1). Both scenarios include projected changes in vehicle numbers and usage on the basis of projections of economic and population growth along with technical changes driven by the imposed air-quality-related emission standards[9].

Imposition of tighter standards results in substantial reductions over baseline emission trends. For example, emissions of both black carbon and NO_x are projected to increase steadily in the developing world after ∼2020 in the baseline scenario, but decrease from 2015 to 2030 in the tight-standard scenario (see Supplementary Information). Globally, vehicle CO and SO_2 emissions decrease moderately by 2030 in the baseline scenario (−3% and −21%), with much larger decreases with tight standards (−43% and −58%). Emissions generally decrease in developed nations under either scenario, but increase in many developing countries in the baseline scenario and in some even with tight standards (owing to growth in the vehicle fleet). We concentrate analyses on 2030 as this often has the minimum emissions given the time for the standards to penetrate the vehicle fleet and the long-term growth in vehicle numbers. The next 20 years is also a timescale over which technology can be reasonably well projected and over which air-quality policies are often considered.

Response to worldwide emission changes

Impacts are calculated using a series of steps: simulation with a global composition–climate model, analysis of the human-health

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Table 1 | Extra vehicle standards in 2015 under the tight-standard scenario.

Region	Light-duty vehicles	Medium- and heavy-duty trucks	Motorcycles
China and India	Euro 6	Euro VI	None
Africa and Middle East	Euro 4	Euro IV	Euro 3
Brazil	Euro 6	Euro VI	Euro 3
Other Latin America	None	None	Euro 3

Euro standards limit emissions of NO_x, hydrocarbons, CO and PM. Accompanying fuel standards (for example on sulphur content) are also included as these are required to meet the emission targets. 'None' means that no extra standards were applied over those in the baseline scenario.

and crop-yield response to concentration changes (not to climate change) and economic valuation of the avoided damage (see Methods). We first explore the response to worldwide baseline and tight vehicle-emission standards, evaluating the climate impact initially using land-area averages of radiative forcing (change in Earth's energy balance with space). The baseline trends cause small net positive forcing (warming) over Africa and the Middle East and much larger negative forcing (cooling) elsewhere (Fig. 1). The positive forcing results from increased black carbon and ozone outweighing negative forcing from increased sulphate (all are within a factor of two). Negative forcing results from reduced black carbon, which has substantial uncertainty, and from multiple other forcings, some of which are positive, leading to large ranges for the net value. Nonetheless, the bulk of the range is clearly negative for many regions.

Imposition of tight standards reduces global mean forcing over land and ocean by $51 \pm 29\,\mathrm{mW\,m^{-2}}$ and leads to negative forcing for all regions over land in 2030 relative to the baseline 2030 emissions (results are significant in all regions examined other than South/Central Africa and North Africa/Middle East (NA/ME)). Forcing decreases even for Western Europe, the Former Soviet Union (FSU) and North America, where emissions were unchanged, reflecting the influence of long-range transport. Impacts of the tight standards are greatest over China, NA/ME, North America, Western Europe and the FSU. Tight standards also produce negative forcing in 2030 relative to 2000 for all regions other than South/Central Africa. The strong geographical contrasts arise from variations in regional climate as well as emissions. For example, over bright snow or desert surfaces, sulphate's effect is minimized as reflective aerosols have a similar albedo to the surface, whereas the effect of absorbing black carbon is enhanced. Despite very similar pollutant concentrations, this can lead to large negative values over the bright Saharan and Arabian deserts and to large positive values over the dark Red Sea in between (see Supplementary Information). Uncertainties in the net forcing also vary strongly from region to region, depending on the relative magnitudes of the individual components (see Supplementary Information).

Imposition of tight standards can also reverse the baseline increase in deaths between 2000 and 2030 owing to vehicle emissions in China, India, Latin America, Africa and the Middle East (Fig. 1). There are also health benefits in areas with no local tightening of emission controls. These are primarily from reduced ozone, which can be transported long distances more easily than PM2.5 (particulate matter smaller than 2.5 μm), in areas far from the emission changes (for example North America), and largely due to PM2.5 in areas nearer the emission changes (for example FSU). The number of avoided deaths varies greatly between regions. Reductions in PM2.5 are usually more important, though ozone generally has a substantial impact in regions straddling the Equator. Globally, the tight-standard scenario leads to ~190,000 (140,000–240,000) avoided deaths per year in 2030 relative to 2000, and roughly 200,000 (120,000–280,000) avoided relative to the baseline scenario. Health benefits are significant in all regions examined.

Crop yield losses due to ozone exposure increase in China, India and Africa under the baseline scenario, whereas they decrease in North America, Western Europe and the FSU. In contrast, the tight-standard scenario leads to reduced losses relative to the year 2000 everywhere other than India (where the losses are still less than in the baseline case). In fact, reductions in yield losses due to the tight standards are largest in percentage for wheat, rice and soybeans in India, and are also large for most crops in NA/ME and China and for soybeans in Latin America, with benefits being significant in all regions examined.

The tight standards substantially reduce economic damage from deaths and crop yield losses (see Methods) in areas where they are applied. The valuations are qualitatively similar to the underlying mortality and crop yield changes. Decreased ozone levels lead to approximately $1.2 billion in annually avoided crop yield losses in China and India alone, with another $550 million in avoided losses in NA/ME and Latin America. Reductions in deaths due to the impact of tight standards on PM2.5 and ozone are valued at $670 billion to $1.1 trillion annually in China and India and $300–380 billion in NA/ME, South & Central Africa and Latin America. Per capita valuation is from approximately $450 to $1300 in these five regions (see Supplementary Information). Valuations of reductions in deaths far from the regions with tighter standards are small, but not negligible: $2 billion in North America, $3–6 billion in Western Europe and $18–28 billion in Western FSU.

Response to regional emission changes

We first examine the impact of local and remote emissions by comparing the responses to regional tight standards on diesel or petrol vehicles and worldwide tight standards. Local 2030 versus 2000 forcing can be greatly influenced by remote emissions (Table 2). For instance, ~60–90% of the reduction in radiative forcing over North America and Western Europe under the tight-standard scenario results from remote emissions (primarily black carbon), making those reductions in radiative forcing substantially greater than under the baseline scenario despite identical local emissions (Fig. 1). For China, local emission controls contribute roughly 40% of the value under worldwide emission changes, with a comparable amount attributable to Indian emission controls. For India, increased emissions in 'rest of world' countries (for example Pakistan, Bangladesh, southeast Asia) lead to strong positive forcing, which offsets ~20% of the impact of local controls. Local emission changes in NA/ME cause positive forcing owing to the very high sulphur content of diesel fuels currently in use there. NA/ME forcing is reduced in the worldwide tight-standard case only because of emission reductions elsewhere, especially nearby India and Western Europe.

Health effects of PM2.5 are often more closely tied to local emissions than is radiative forcing. For North America, Western Europe and China, roughly 80–95% of the benefits under the tight-standard scenario result from local controls (Table 2). Reduced international transport of pollution is important, however, enhancing benefits in China by ~20% and in NA/ME by ~50%. Changes in PM2.5-related premature deaths in India follow a similar pattern to radiative forcing, with benefits of local controls being partially offset by emission increases in other countries. PM2.5-related health benefits are generally greater for diesel- than petrol-vehicle controls. Regional sensitivity for ozone-related premature deaths is geographically broader than for PM2.5, consistent with ozone's longer lifetime (Table 2). For India, increased emissions in neighbouring countries have a greater impact than local controls, leading to a net increase in ozone-related premature deaths under the worldwide tight-standard scenario (see Supplementary Information).

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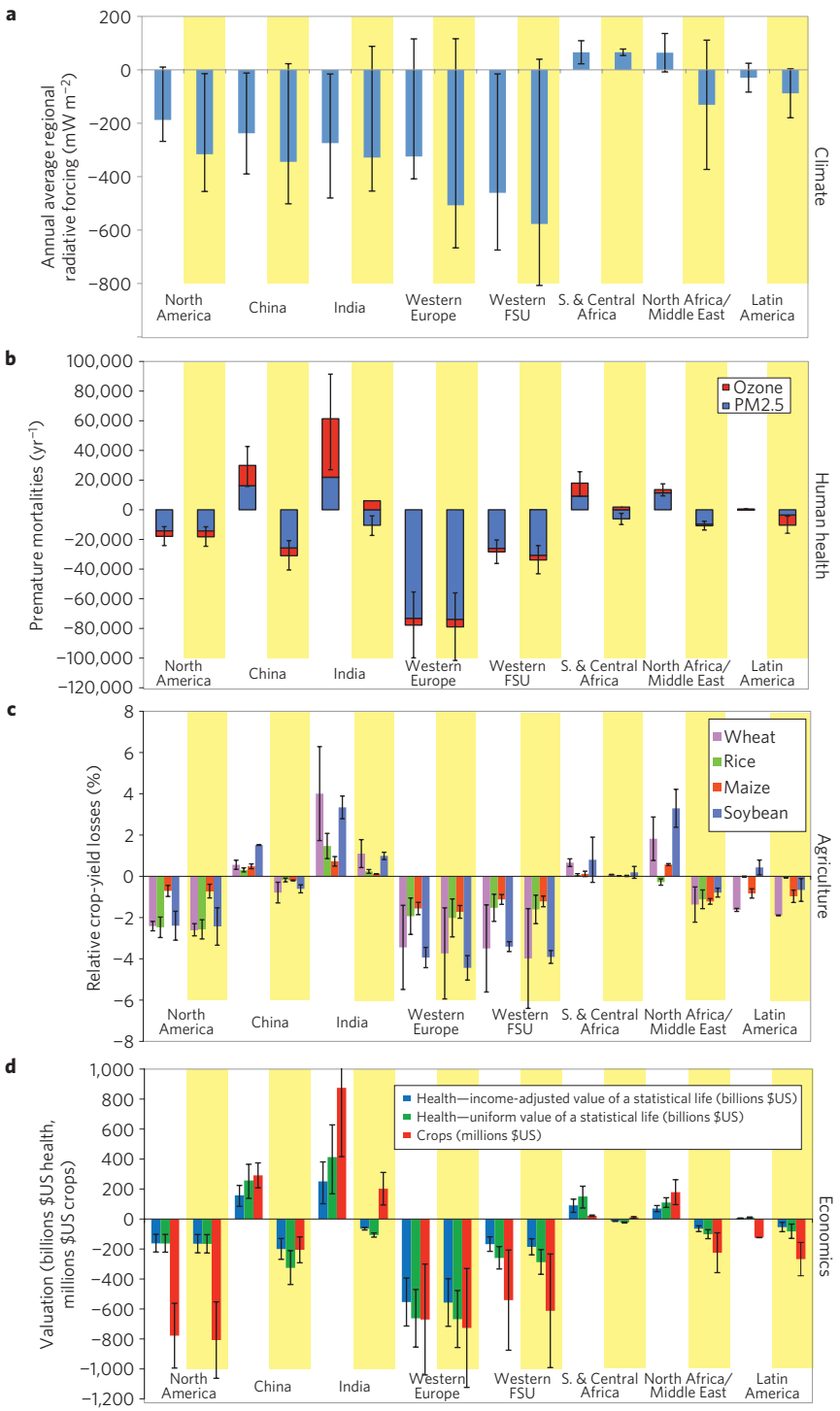

Figure 1 | Impacts of worldwide vehicle emissions in 2030 compared with 2000. a–d, Changes are shown under the baseline (left side by region) and tight-standard scenarios (yellow, right side by region). Negative valuations indicate savings. Ranges include the estimated forcing uncertainty on the basis of published observations and modelling results (**a**, ~67% confidence interval (CI); see Supplementary Information), uncertainty due to concentration–response relationships only (**b**, health; **d**, health valuation; 95% CI) and uncertainty due to concentration–response metrics (**c**, crops; for crop valuation see Supplementary Information). Much of the uncertainty is systematic, so differences between scenarios can be significant even if uncertainty ranges for the two scenarios overlap (see Supplementary Information).

Crop yield losses in North America and Western Europe show similar patterns to those seen for ozone-related deaths, with ~65–90% of local benefits resulting from local emissions. For China and India, the effect of remote emissions on crops is large, but differs from that seen for health (in percentage terms, relative to local emissions; see Supplementary Information). As with ozone-related deaths, the crop impacts of petrol- and diesel-vehicle-emission changes are comparable for North America and Western Europe, whereas diesel-vehicle-emission controls are much more beneficial in India and

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Table 2 | Regional impacts in 2030 relative to 2000 under the tight-standard scenario.

Impact and impact region	Total response	Percentage of response due to emission change in these regions							
		Local petrol	Local diesel	North America	Western Europe	China	India	NA/ME	Rest of world
Radiative forcing	mW m^{-2}								
North America	−316	−13	19	**6**	39	8	7	−1	39
Western Europe	−507	0	36	21	**36**	3	3	0	37
China	−345	26	12	13	22	**38**	42	−2	−13
India	−329	67	41	9	13	9	**108**	−17	−21
NA/ME	−131	8	−70	24	43	9	49	**−62**	37
Avoided PM2.5 deaths	yr^{-1}								
North America	14,000	42	49	**91**	<1	<1	<1	<1	9
Western Europe	73,000	21	74	<1	**96**	<1	<1	<1	4
China	26,000	13	66	1	2	**79**	1	2	16
India	10,000	10	287	1	1	2	**297**	28	−228
NA/ME	10,000	8	39	<1	8	<1	1	**47**	45
Avoided ozone deaths	yr^{-1}								
North America	4,000	43	39	**82**	4	<1	1	<1	13
Western Europe	5,000	34	45	10	**79**	1	1	−1	10
China	5,000	−2	55	30	30	**53**	7	−2	−17
India	−6,000	35	−147	−26	−14	−4	**−112**	6	249
NA/ME	1,000	6	−76	42	75	4	10	**−70**	39
Mean wheat-yield increase	Million tonnes (%)								
North America	2.2 (2.3)	45	42	**87**	6	<1	2	<1	5
Western Europe	5.6 (3.8)	34	45	14	**79**	1	1	<1	5
China	0.9 (0.8)	1	19	24	26	**20**	4	−1	27
India	−1.0 (−1.1)	11	−57	−18	−12	−2	**−46**	5	173
NA/ME	0.4 (1.3)	10	−89	45	55	2	5	**−79**	72

Total impacts of local diesel- and petrol-vehicle-emission changes on the region of emission are given in bold and are the sum of the separate impacts of local petrol and diesel changes. Values in the six right columns hence include all changes. Yield changes for wheat are shown as an example, with values for other crops given in Supplementary Information.

China. Valuation of crop losses and deaths would follow the relative contribution of each region and fuel type to the underlying impacts (Table 2).

We now examine the effect of the extra emission controls, and how much change might be obtained during the next two decades (2010 differs substantially from 2000 in some regions, though we also use 2000 because emission inventories are better established for that time). The global forcing reduction due to tight emission standards in 2030 compared with 2010 emissions is large for diesel vehicles in India and Latin America (diesel controls were only applied in Brazil), modest for petrol vehicles in India and petrol or diesel vehicles in China, and small for other regions/fuels (Fig. 2). Emissions from Indian diesel vehicles have particularly large climate impacts owing to their proximity to highly reflective snow/ice and desert areas. Controls on Brazilian diesel have an enhanced effect in part due to the large ozone response owing to plentiful sunlight. Examining the forcing in 2030 under the two scenarios indicates that ∼1/2–2/3 of the petrol vehicle forcing reductions in China and India are expected under the baseline case. Similarly, forcing reductions due to decreased Chinese diesel emissions over 2010–2030 are exclusively due to the baseline changes, with tighter standards inducing positive forcing through reduced organic carbon.

Analyses of radiative forcing by vehicle type show that maximum forcing reductions in 2030 with tight standards relative to the baseline come from emission controls on heavy-duty diesel trucks in India and Brazil, medium-duty diesel vehicles in India and light-duty petrol vehicles in NA/ME (Fig. 2). Small extra reductions come from controls on light-duty petrol vehicles everywhere, and in some regions from controls on motorcycles and medium-duty trucks. Controls on diesel vehicles in Western Europe, petrol cars and heavy-duty trucks in North America and motorcycles in India and China that take place under either scenario provide substantial forcing reductions, indicating that full implementation of currently planned emission controls is important for climate. The net forcing depends strongly on the balance between multiple components, underscoring the need for analysis across all emitted compounds.

Climate response to vehicle emissions

We examine temperature changes induced by the non-CO_2 vehicle emissions using global[10] and regional temperature potentials[11] (see Supplementary Information). The latter provide reasonable estimates by latitude band, an appropriate region because the temperature response to forcing occurs primarily within ∼30° in latitude, but extends very far in longitude[12]. The baseline scenario shows cooling for approximately the next 20 years due primarily to sulphur (Fig. 3). The worldwide tight standards eliminate this cooling by reducing sulphur emissions, which is required for efficient use of particle filters. This is similar to the 'bumpy road' of climate response to controls on all sectors[13]. From ∼30–40 years

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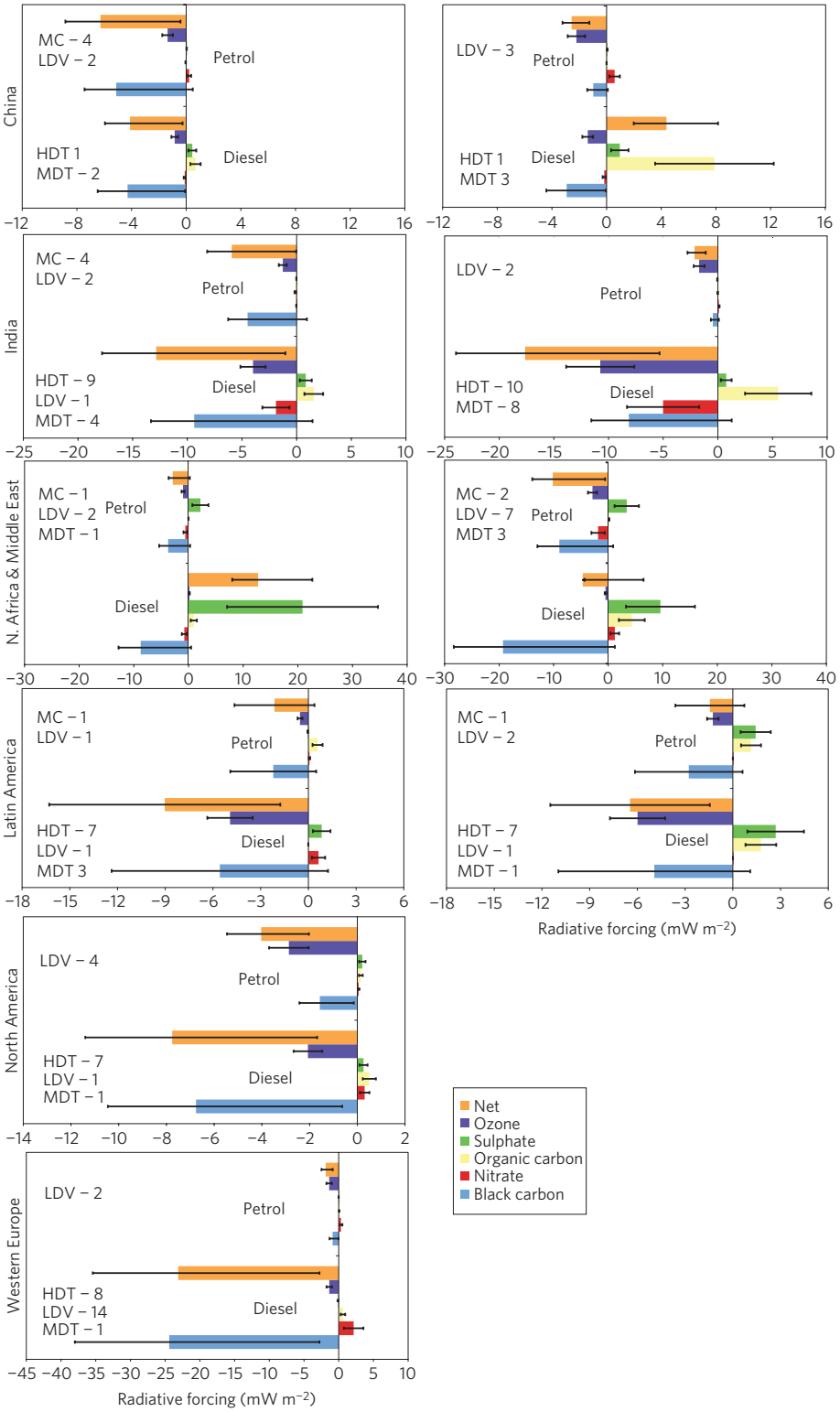

Figure 2 | Net and per-component global mean radiative forcing (mW m^{-2}) by region and fuel type. Values are 2030 forcing with tight standards on diesel or petrol vehicles in the given region relative to 2010 (left column) and relative to the 2030 baseline scenario (right column). Inset numbers give net forcing by vehicle type due to all agents except sulphate. Uncertainties for forcing by vehicle type scale with the net for that region and fuel. Latin American results are taken from the worldwide emission-change simulations because remote emissions contribute less than 2% of forcing there (unlike other regions (Table 2)). MC, motorcycles; LDV, light-duty vehicles; MDT, medium-duty trucks; HDT, heavy-duty trucks.

onwards, the baseline emissions lead to warming relative to the present, especially at northern latitudes with large black carbon forcings. The tight standards lead to only a small reduction in global warming post 2040. The tight standards do, however, turn a northern Hemisphere mid-latitude warming of 0.07 °C (0.02 to 0.12) °C into a cooling of 0.15 (0.02 to 0.26) °C, and change

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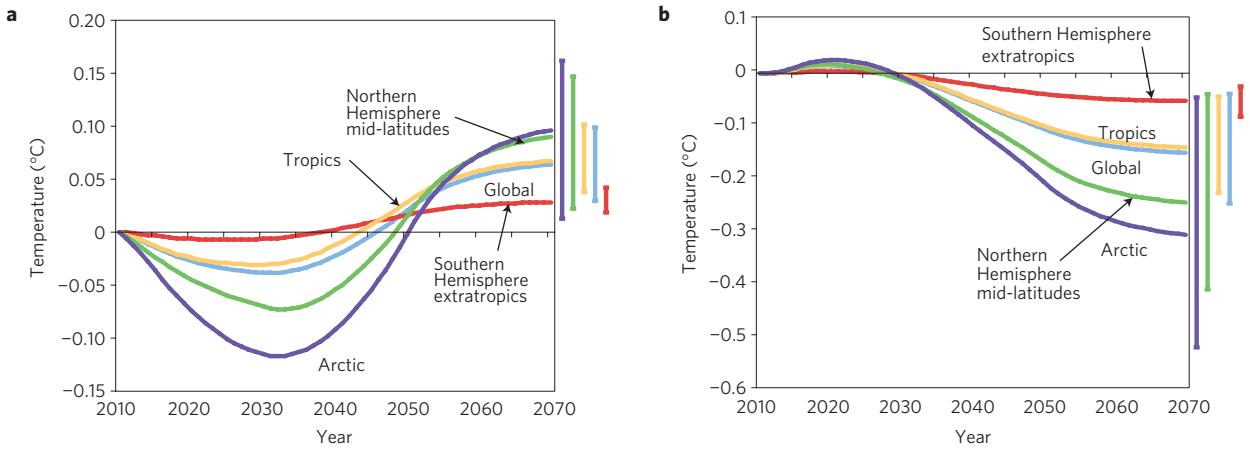

Figure 3 | Climate response to non-CO_2 vehicle emissions. a,b, Global and regional zonal mean temperature changes relative to 2010 due to non-CO_2 vehicle emissions under the baseline scenario (**a**) and the difference between the tight-standard and baseline scenarios (**b**). Bars on the right show uncertainty ranges for 2070, including contributions from both forcing and climate sensitivity (67%; CI).

an Arctic warming of 0.07 (0.01 to 0.12) °C into a cooling of −0.21 (0.03 to −0.35) °C over the next 50 years. The substantial uncertainties are largely from black carbon, which has poorly quantified indirect effects on clouds and albedo. Uncertainty in climate sensitivity also contributes, and hence if future warming due to CO_2 is large the climate benefit of these measures will also tend to be large. From a risk perspective, that most of the range of temperature changes shows substantial values is more important than a small portion of the range being consistent with very small impacts. Note that, despite the small probability that the large-scale changes are near zero, regional climate benefits are still very likely as black carbon affects circulation patterns such as the monsoons and increases melting of snow and ice[14–17].

In addition to meteorological changes induced by aerosols or ozone, microphysical interactions between aerosols and clouds can drive precipitation changes[16–21]. In long climate simulations (see Supplementary Information), tight standards on diesel vehicles in China cause increased precipitation over southeast China and southeast Asia, but decreases in Japan. Such results are not yet robust, but highlight how multiple aspects of climate will be affected by emission policies. Changes in water supply, drought frequency and soil erosion can have substantial impacts, and merit further study.

The multiple benefits of tighter standards

Gases and particles both substantially influence radiative forcing and premature deaths. Hence policies should consider the effects of all emitted compounds. Diesel-vehicle-emission trends in NA/ME lead to warming even with tight standards owing to fuel desulphurization (though less warming than in the baseline scenario). In China, tightening diesel standards leads to positive forcing due to elimination of large baseline increases in organic carbon, though net forcing relative to 2010 is still negative (and health/agriculture benefits are large). In other regions, reduced emissions from either petrol or diesel vehicles under our tight-standard scenario always mitigate 2030 forcing (relative to 2010 or relative to the 2030 baseline). Hence in nearly all cases tightening of emission standards would achieve multiple goals rather than advancing some whereas setting back others.

Our study shows that current vehicle-emission trends, if fully implemented, will substantially decrease radiative forcing, premature deaths and ozone-related agricultural yield losses for North America and Europe, with the opposite for Africa and the Middle East. For China, India and Latin America, the current path reduces forcing but increases deaths and ozone-related agricultural yield losses (the latter is crop dependent for Latin America). Tightening vehicle standards in the developing world leads to a decrease in forcing, deaths and agricultural yield losses nearly everywhere. Although implementing emission-control technologies, monitoring and enforcement carry substantial costs, the value of the health and agricultural benefits is very large. As health and agricultural benefits are typically greatest where controls are tightened, the local benefit–cost ratio may be quite favourable for adoption of tight standards. Climate benefits are felt more broadly than air-quality improvements, and have much larger uncertainties, but consideration of the climate benefits could help generate extra support for what have traditionally been regarded as purely air-quality regulations. The greatest climate benefits come from controls on diesel trucks in Brazil and India and on petrol vehicles in NA/ME.

The emission standards examined here do not directly affect CO_2, emissions of which from vehicles are projected to increase substantially[3,9]. Strategies such as increased fuel efficiency, mode switching (for example truck to rail, cars to mass transit) or electrification of vehicles (powered by renewable energy) are required to reduce CO_2 emissions and long-term climate change, and would complement the emission standards examined here. Our results support previous studies[22,23] indicating that the substantial benefits for both climate and public health can be maximized by carefully constructed emission-control policies.

Methods

The global composition–climate model used is the GISS (Goddard Institute for Space Studies) Model for Physical Understanding of Composition–Climate Interactions and Impacts (G-PUCCINI), incorporating gas-phase and aerosol chemistry within the ModelE climate model[24]. G-PUCCINI was run at 2° latitude by 2.5° longitude resolution with 40 vertical layers up to 0.1 hPa. Aerosols are externally mixed, but we include a 50% increase in absorption by black carbon to account for internal mixing with other aerosols[25]. Constant year-2000 emissions[26] were used for all sources other than on-road vehicles. Simulations were carried out for 2030 changing all vehicle emissions worldwide simultaneously according to our scenarios, followed by separate runs to analyse the effects of tight standards in 2030 by fuel type for five regions of the world: North America, Western Europe, NA/ME, India and China (see Supplementary Information).

Direct ozone and aerosol forcings (instantaneous tropopause values) were calculated within the climate model. Aerosol indirect effects, including impacts on clouds and snow–ice albedo, are highly uncertain[27,28] and hence not robustly characterized using a single model. We include the aerosol indirect effects, adjustments to black carbon direct forcing and uncertainties on the basis of recent assessments of both models and observations (see Supplementary Information). We also examined forcings by long-lived greenhouse gases, although

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these were very small (see Supplementary Information). Global and regional climate responses are calculated using simple energy-balance equations derived from coupled ocean–atmosphere models[10,29] (see Supplementary Information). Temperature ranges include both uncertainty in the driving radiative forcing and in climate sensitivity[30].

Analyses of radiative forcing by vehicle type (classes of cars, trucks and motorcycles) use the response per unit precursor emission in the regional perturbation experiments for each species multiplied by the vehicle-type-specific emission change (except for sulphur, whose emissions were not available by vehicle type; see Supplementary Information). For petrol vehicles, sulphate contributes little to forcing. For diesel, we omit forcing by vehicle type for NA/ME, where sulphate forcing is quite important. Similar analyses are not carried out for other impacts as it is even more difficult to linearly relate emissions to PM2.5 or to daily or seasonal ozone maxima.

Human-health impacts are based on reported concentration–response relationships applied to the annual mean modelled surface PM2.5 exposure and the 6 month maximum of the averaged 1 h daily maximum ozone concentrations for the projected 2030 population. Modelled PM2.5 distributions were downscaled to $0.5° \times 0.5°$ using a subgrid parameterization of urban/rural differences (see Supplementary Information). We include PM mortalities due to cardiopulmonary illness and lung cancer calculated using relative-risk estimates[31] and ozone mortalities calculated using relative-risk estimates for respiratory disease from a two-pollutant model[32]. The 95% confidence intervals of the concentration–response relationships are used, but other sources of uncertainty (see Supplementary Information) are not included. The total impact of air pollution from this methodology is reasonably consistent with previous estimates[33,34] (see Supplementary Information).

Ozone-related crop-yield changes were calculated for wheat, rice, maize and soybeans following from previous work[35]. To characterize uncertainty, we use two sets of concentration–response metrics, maximum 7 or 12 h mean ozone exposures and accumulated ozone over 40 ppbv threshold (AOT40) applied to modelled ozone (see Supplementary Information). Note that the Western FSU group includes all of Russia for crop impacts as analyses were only available on a country-by-country basis. Valuation of crop yield changes uses year-2000 global market prices from the Food and Agriculture Organization (http://faostat.fao.org), which clearly does not account for benefits such as those to subsistence farmers or to national food security.

Valuation of premature mortalities is based on the value of a statistical life (VSL) approach[36,37]. The relationship between mortality risks and willingness to pay (WTP) is used to determine the VSL, which is an expression of the value that people affix to small changes in mortality risks in monetary terms. We employ the US Environmental Protection Agency's (USEPAs) preferred VSL of $9,500,000 for 2030. This value represents the mean of 26 peer-reviewed studies[38], inflated to 2030 on the basis of projected income growth.

Our first approach applies the USEPA value uniformly across all countries, so that mortality risks are valued equally worldwide. Although ethically appealing, the VSL is based on society's WTP for mortality risk reduction and WTP is a function of income. Hence, it is likely that WTP will vary by country. This motivates the second approach in which the USEPA VSL is adjusted. We employ the USEPA's elasticity of 0.40 between income and WTP to estimate country-specific VSLs on the basis of the relationship between country-specific income per capita and that in the US (ref. 38) using income data reported by the World Bank[39] (see Supplementary Information).

Valuation for other effects of air quality, such as changes in forestry yields, tourism or depreciation of man-made materials, is not included, nor are costs associated with climate change. Hence our valuations are perhaps conservative, though the valuation of human health tends to dominate[40].

Received 9 December 2010; accepted 28 February 2011; published online 29 March 2011

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Acknowledgements

We thank the NASA Applied Sciences program, the ClimateWorks Foundation and the California Air Resources Board for supporting this work. We also thank T. Bond for gridding the emissions, M. Brauer for providing the PM2.5-measurement database, J. West for assistance with the population projection, B. Croes and D. Luo at CARB for their assistance and the UNEP/WMO Integrated Assessment of Black Carbon and Tropospheric Ozone team for discussions. Conclusions expressed in this article are the authors and do not necessarily represent those of their employers.

Author contributions

D.S. planned and led the work and writing of the paper. G.F. carried out the composition–climate modelling. M.W. carried out the emissions analyses. S.C.A. and J.A. carried out the health analyses. R.V.D. carried out the crop-yield and valuation analysis. N.Z.M. carried out the health valuation analysis. D.K. provided input on aerosol modelling. G.M. analysed the composition–climate model output. All contributed to writing the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to D.S.

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