Short-Lived Climate Pollutant Research Digest

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CLIMATE & CLEAN AIR COALITION
TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

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Multiple Benefits/Impacts & Crosscutting

Description: This section includes articles addressing the multiple benefits of action to address SLCPs and implement SLCP measures.

Population health impacts of China's climate change policies

Rapid and wide-ranging reductions in greenhouse gas emissions are required to meet the climate targets agreed upon at the 2015 Paris climate conference. There will be significant transition risks for health, livelihoods, and ecosystems associated with large-scale mitigation, but also opportunities. The aim of this study was to investigate the impacts, positive and negative, of climate policies on population health in China. We review the Intended Nationally Determined Contribution (INDC) that China took to the Paris meeting, link commitments in the INDC to national planning documents relevant to environment and health, and search the literature for Chinese publications on health trade-offs and synergies. Synergies are evident in the measures taken to reduce local air pollution in China: controls on coal burning have materially improved local air quality and benefited health. But there may be risks to health also, depending on how policies are implemented and what safeguards are provided. To date most assessments of the health impacts of climate policies in China have been modelling studies. We recommend work of this kind is complemented by observational research to identify unexpected impacts and vulnerabilities. It will become even more important to undertake this work as emission reductions accelerate to meet the Paris climate targets.

Woodward, A., Baumgartner, J., Ebi, K. L., Gao, J., Kinney, P. L., & Liu, Q. (2019). Population health impacts of China's climate change policies. Environmental research, 175, 178-185.

Methane

Description: This section includes articles addressing methane source apportionment, emissions factors, impacts and emissions trends.

Atmospheric dispersion of methane emissions from sugarcane burning in Mexico

Methane is a potent greenhouse gas whose atmospheric dispersion may have different implications at distinct scales. One significant contributor to methane emissions is sugarcane farming in tropical areas like in Mexico, which has the sixth highest production level in the world. A consequence of the industrial use of this resource is that sugarcane preharvest burning emits large quantities of methane and other pollutants. The objective of this research is to estimate the methane emissions by sugarcane burning and to analyze their atmospheric dispersion under the influence of meteorological parameters, according to different concentration scenarios generated during a period. The methane emissions were investigated using the methodology of Seiler and Crutzen, based on the stage production during the harvest periods of 2011/2012, 2012/2013 and 2013/2014. Average of total emissions (1.4 × 103 Mg) at the national level was comparable in magnitude to those of other relevant sugarcane-producing countries such as India and Brazil. Satellite images and statistical methods were used to validate the spatial distribution of methane, which was obtained with the WRF model. The results show a dominant wind circulation pattern toward the east in the San Luis Potosi area, to the west in Jalisco, and the north in Tabasco. In the first two areas, wind convergence at a certain height causes a downward flow, preventing methane dispersion. The concentrations in these areas varied from 9.22 × 10−5 to 1.22 × 102 ppmv and 32 × 10−5 to 2.36 × 102 ppmv, respectively. Wind conditions in Tabasco contributed to high dispersion and low concentrations of methane, varying from 8.74 × 105 to 0.33 × 102 ppmv. Methane is a potent greenhouse gas for which it is essential to study and understand their dispersion at different geographic locations and atmospheric conditions.

Flores-Jiménez, D. E., Carbajal, N., Algara-Siller, M., Aguilar-Rivera, N., Álvarez-Fuentes, G., Ávila-Galarza, A., & García, A. R. (2019). Atmospheric dispersion of methane emissions from sugarcane burning in Mexico.

Environmental Pollution, 250, 922-933.

Large Fugitive Methane Emissions From Urban Centers Along the U.S. East Coast

Urban emissions remain an underexamined part of the methane budget. Here we present and interpret aircraft observations of six old and leak-prone major cities along the East Coast of the United States. We use direct observations of methane (CH4), carbon dioxide (CO2), carbon monoxide (CO), ethane (C2H6), and their correlations to quantify CH4 emissions and attribute to natural gas. We find the five largest cities emit 0.85 (0.63, 1.12) Tg CH4/year, of which 0.75 (0.49, 1.10) Tg CH4/year is attributed to natural gas. Our estimates, which include all thermogenic methane sources including end use, are more than twice that reported in the most recent gridded EPA inventory, which does not include end-use emissions. These results highlight that current urban inventory estimates of natural gas emissions are substantially low, either due to underestimates of leakage, lack of inclusion of end-use emissions, or some combination thereof.

Plant, G., Kort, E. A., Floerchinger, C., Gvakharia, A., Vimont, I., & Sweeney, C. (2019). Large fugitive methane emissions from urban centers along the US East Coast. Geophysical Research Letters, 46(14), 8500-8507.

Atmospheric Methane Emissions Correlate With Natural Gas Consumption From Residential and Commercial Sectors in Los Angeles

Legislation in the State of California mandates reductions in emissions of short-lived climate pollutants of 40% from 2013 levels by 2030 for CH4. Identification of the sector(s) responsible for these emissions and their temporal and spatial variability is a key step in achieving these goals. Here, we determine the emissions of CH4 in Los Angeles from 2011–2017 using a mountaintop remote sensing mapping spectrometer. We show that the pattern of CH4 emissions contains both seasonal and nonseasonal contributions. We find that the seasonal component peaks in the winter and is correlated (R2 = 0.58) with utility natural gas consumption from the residential and commercial sectors and not from the industrial and gas-fired power plant sectors. The nonseasonal component is (22.9 ± 1.4) Gg CH4/month. If the seasonal correlation is causal, about (1.4 ± 0.1)% of the commercial and residential natural gas consumption in Los Angeles is released into the atmosphere.

He, L., Zeng, Z. C., Pongetti, T. J., Wong, C., Liang, J., Gurney, K. R., ... & Duren, R. (2019). Atmospheric methane emissions correlate with natural gas consumption from residential and commercial sectors in Los Angeles. Geophysical Research Letters, 46(14), 8563-8571.

Methane budget of East Asia, 1990–2015: A bottom-up evaluation

The regional budget of methane (CH4) emissions for East Asia, a crucial region in the global greenhouse gas budget, was quantified for 1990–2015 with a bottom-up method based on inventories and emission model simulations. Anthropogenic emissions associated with fossil fuel extraction, industrial activities, waste management, and agricultural activities were derived from the Emission Database for Global Atmospheric Research version 4.3.2 and compared with other inventories. Emissions from natural wetlands and CH4 uptake by upland soil oxidation were estimated using the Vegetation Integrative SImulator for Trace gases (VISIT), a biogeochemical model that considers historical land use and climatic conditions. Emissions from biomass burning and termites were calculated using satellite and land-use data combined with empirical emission factors. The resulting average annual estimated CH4 budget for 2000–2012 indicated that East Asia was a net source of 67.3 Tg CH4 yr−1, of which 88.8% was associated with anthropogenic emissions. The uncertainty (±standard deviation) of this estimate, ±14 Tg CH4 yr−1, stemmed from data and model inconsistencies. The increase of the net flux from 60.2 Tg CH4 yr−1 in 1990 to 78.0 Tg CH4 yr−1 in 2012 was due mainly to increased emissions by the fossil fuel extraction and livestock sectors. Our results showed that CH4 was a crucial component of the regional greenhouse gas budget. A spatial analysis using 0.25° × 0.25° grid cells revealed emission hotspots in urban areas, agricultural areas, and wetlands. These hotspots were surrounded by weak sinks in upland areas. The estimated natural and anthropogenic emissions fell within the range of independent estimates, including top-down estimates from atmospheric inversion models. Such a regional accounting is an effective way to

elucidate climatic forcings and to develop mitigation policies. Further studies, however, are required to reduce the uncertainties in the budget.

Ito, A., Tohjima, Y., Saito, T., Umezawa, T., Hajima, T., Hirata, R., ... & Terao, Y. (2019). Methane budget of East Asia, 1990–2015: A bottom-up evaluation. Science of The Total Environment, 676, 40-52.

Black Carbon

Description: This section includes articles addressing black carbon source apportionment, emissions factors, impacts and emissions trends.

Personal exposure to black carbon in Stockholm, using different intra-urban transport modes

The traffic microenvironment has been shown to be a major contributor to the total personal exposure of black carbon (BC), and is key to local actions aiming at reducing health risks associated with such exposure. The main aim of the study was to get a better understanding of the determinants of traffic-related personal exposure to BC in an urban environment.

Personal exposure to ambient levels of BC was monitored while walking, cycling and traveling by bus or car along four streets and while cycling alternative routes simultaneously. Monitoring was performed during morning and afternoon peak hours and at midday, with a portable aethalometer recording one-minute mean values. In all, >4000 unique travel passages were performed. Stepwise Linear Regression was used to assess predictors to personal exposure levels of BC.

The personal BC concentration ranged 0.03–37 µg/m3. The average concentrations were lowest while walking (1.7 µg/m3) and highest traveling by bus (2.7 µg/m3). However, only 22% of the variability could be explained by travel mode, urban background BC and wind speed. BC concentrations measured inside a car were on average 33% lower than measured simultaneously outside the car. Choosing an alternative bicycle route with less traffic resulted in up to 1.4 µg/m3 lower personal exposure concentrations.

In conclusion, traveling by bus rendered the highest personal BC concentrations. But when taking travel time and inhalation rate into account, the travel-related exposure dose was predicted to be highest during walking and cycling. It is however probable that the benefits from physical activity outweigh health risks associated with this higher exposure dose.

It is clear that road traffic makes an important contribution to personal exposure to BC regardless of mode of intra-urban transport. Our data suggest that commuting along routes with lower BC levels would substantially decrease commuter's exposure.

Merritt, A. S., Georgellis, A., Andersson, N., Bedada, G. B., Bellander, T., & Johansson, C. (2019). Personal exposure to black carbon in Stockholm, using different intra-urban transport modes. Science of the Total Environment, 674, 279-287.

Tropospheric Ozone

Description: This section includes articles addressing tropospheric ozone impacts and important trends in precursor emissions.

Short-term responses of greenhouse gas emissions and ecosystem carbon fluxes to elevated ozone and N fertilization in a temperate grassland

Growing evidence suggests that tropospheric ozone has widespread effects on vegetation, which can contribute to alter ecosystem carbon (C) dynamics and belowground processes. In this study, we used intact soil mesocosms from a semi-improved grassland and investigated the effects of elevated ozone, alone and in combination with nitrogen (N) fertilization on soil-borne greenhouse gas emissions and ecosystem C fluxes. Ozone exposure under

fully open-air field conditions was occurred during the growing season. Across a one-year period, soil methane (CH4) and nitrous oxide (N2O) emissions did not differ between treatments, but elevated ozone significantly depressed soil CH4 uptake by 14% during the growing season irrespective of N fertilization. Elevated ozone resulted in a 15% reduction of net ecosystem exchange of carbon dioxide, while N fertilization significantly increased ecosystem respiration during the growing season. Aboveground biomass was unaffected by elevated ozone during the growing season but significantly decreased by 17% during the non-growing season. At the end of the experiment, soil mineral N content, net N mineralization and extracellular enzyme activities (i.e., cellobiohydrolase and leucine aminopeptidase) were higher under elevated ozone than ambient ozone. The short-term effect of single application of N fertilizer was primarily responsible for the lack of the interaction between elevated ozone and N fertilization. Therefore, results of our short-term study suggest that ozone exposure may have negative impacts on soil CH4 uptake and C sequestration and contribute to accelerated rates of soil N-cycling.

Wang, J., Hayes, F., Chadwick, D. R., Hill, P. W., Mills, G., & Jones, D. L. (2019). Short-term responses of greenhouse gas emissions and ecosystem carbon fluxes to elevated ozone and N fertilization in a temperate grassland. Atmospheric Environment, 211, 204-213.

Socio-Economic impacts

Description: This section includes articles addressing the socio-economic impacts due to air pollutions and SLCP related climate changes

Which decreases in air pollution should be targeted to bring health and economic benefits and improve environmental justice?

Fine particulate matter (PM2.5) exposure entails large health effects in many urban areas. Public measures aiming at decreasing air pollution are often designed without targeting an explicit health benefit. Our objective was to investigate the health and economic benefits and the social inequalities in exposure resulting from several scenarios of reduction of PM2.5 exposure, in order to support decisions about urban policies.

In the French conurbations of Grenoble and Lyon (0.4 and 1.4 million inhabitants, respectively), PM2.5 yearly average exposure was estimated on a 10-m grid by coupling a PM2.5 dispersion model to population density. Changes in death cases, life expectancy, lung cancer and term low birth weight incident cases as well as associated health economic costs were estimated for ten PM2.5 reduction scenarios differing in terms of amplitude of reduction and spatial extent. Changes in social differences in PM2.5 exposure were also assessed.

During the 2015–2017 period, PM2.5 average exposure was 13.9 µg/m3 in Grenoble and 15.3 µg/m3 in Lyon conurbations. Exposure to PM2.5 led to an estimated 145 (95% Confidence Interval, CI, 90–199) and 531 (95% CI, 330–729) premature deaths, 16 (95% CI, 8–24) and 65 (95% CI, 30–96) incident lung cancers, and 49 (95% CI, 19–76) and 193 (95% CI, 76–295) term low birth weight cases each year in Grenoble and Lyon conurbations, respectively, compared to a situation without PM2.5 anthropogenic sources, i.e. a PM2.5 concentration of 4.9 µg/m3. The associated costs amounted to 495 (Grenoble) and 1767 (Lyon) M€/year for the intangible costs related to all-cause non-accidental mortality and 27 and 105 M€ for the tangible and intangible costs induced by lung cancer. A PM2.5 exposure reduction down to the WHO air quality guideline (10 µg/m3) would reduce anthropogenic PM2.5-attributable mortality by half while decreases by 2.9 µg/m3 (Grenoble) and 3.3 µg/m3 (Lyon) were required to reduce it by a third. Scenarios focusing only on the most exposed areas had little overall impact. Scenarios seeking to reach a homogeneous exposure in the whole study area were the most efficient in alleviating social inequalities in exposure.

Reduction scenarios targeting only air pollution hotspots had little expected impact on population health. We provided estimates of the PM2.5 change required to reduce PM2.5-attributable mortality by one third or more. Our approach can help targeting air pollution reduction scenarios expected to entail significant benefits, and it could easily be transposed to other urban areas.

Morelli, X., Gabet, S., Rieux, C., Bouscasse, H., Mathy, S., & Slama, R. (2019). Which decreases in air pollution should be targeted to bring health and economic benefits and improve environmental justice?. Environment international, 129, 538-550.

Biomass Burning & Household Energy

Description: This section includes articles primarily addressing SLCP measures and innovations related to the household energy initiative, open burning of agricultural residue, and SLCP emissions in relevant sectors. Solid waste burning is covered in the waste section.

Household air pollution mitigation with integrated biomass/cookstove strategies in Western Kenya

Traditional cooking is today's largest global environmental health risk. Over 640 million people in Africa are expected to rely on biomass for cooking by 2040. In Kenya, cooking inefficiently with wood and charcoal persists as a cause of deforestation and household air pollution. This research analyses the effects of four biomass cookstove strategies on reducing air pollutant emissions in Kisumu County between 2015 and 2035 using the Long-Range Energy Alternatives Planning system. The Business as Usual scenario (BAU) was developed considering the historical trends in household energy use. Energy transition scenarios to Improved Cookstoves (ICS), Pellet Gasifier Stoves (PGS) and Biogas Stoves (BGS) were applied to examine the impact of these systems on energy savings and air pollution mitigation. An integrated scenario (INT) was evaluated as a mix of the ICS, PGS and BGS. The highest energy savings, in relation to the BAU, are achieved in the BGS (30.9%), followed by the INT (23.5%), PGS (19.4%) and ICS (9.2%). The BGS offers the highest reduction in the GHG (37.6%), CH4 (94.3%), NMVOCs (85.0%), CO (97.4%), PM2.5 (64.7%) and BC (48.4%) emissions, and the PGS the highest reduction in the N2O (83.0%) and NOx (90.7%) emissions, in relation to the BAU.

Carvalho, R. L., Lindgren, R., García-López, N., Nyambane, A., Nyberg, G., Diaz-Chavez, R., & Boman, C. (2019). Household air pollution mitigation with integrated biomass/cookstove strategies in Western Kenya. Energy Policy, 131, 168-186.

Effects and acceptability of implementing improved cookstoves and heaters to reduce household air pollution: a FRESH AIR study

The objective was to evaluate the effectiveness and acceptability of locally tailored implementation of improved cookstoves/heaters in low- and middle-income countries. This interventional implementation study among 649 adults and children living in rural communities in Uganda, Vietnam and Kyrgyzstan, was performed after situational analyses and awareness programmes. Outcomes included household air pollution (PM2.5 and CO), self-reported respiratory symptoms (with CCQ and MRC-breathlessness scale), chest infections, school absence and intervention acceptability. Measurements were conducted at baseline, 2 and 6–12 months after implementing improved cookstoves/heaters. Mean PM2.5 values decrease by 31% (to 95.1 µg/m3) in Uganda (95%CI 71.5–126.6), by 32% (to 31.1 µg/m3) in Vietnam (95%CI 24.5–39.5) and by 65% (to 32.4 µg/m3) in Kyrgyzstan (95%CI 25.7–40.8), but all remain above the WHO guidelines. CO-levels remain below the WHO guidelines. After intervention, symptoms and infections diminish significantly in Uganda and Kyrgyzstan, and to a smaller extent in Vietnam. Quantitative assessment indicates high acceptance of the new cookstoves/heaters. In conclusion, locally tailored implementation of improved cookstoves/heaters is acceptable and has considerable effects on respiratory symptoms and indoor pollution, yet mean PM2.5 levels remain above WHO recommendations.

van Gemert, F., de Jong, C., Kirenga, B., Musinguzi, P., Buteme, S., Sooronbaev, T., ... & Quynh, N. N. (2019). Effects and acceptability of implementing improved cookstoves and heaters to reduce household air pollution: a FRESH AIR study. NPJ primary care respiratory medicine, 29(1), 1-9.

Agriculture and Livestock

Description: This section includes articles primarily addressing SLCP measures and innovations related to the Agriculture initiative and SLCP emissions in relevant sectors

Methane emissions of stored manure from dairy cows fed conventional or brown midrib corn silage

The objective of this study was to examine the effects of feeding conventional corn silage (CCS) or brown midrib corn silage (BMCS) to dairy cows on CH4 emissions from stored manure. Eight lactating cows were fed (ad libitum) a total mixed ration (forage:concentrate ratio 65:35; dry matter basis) containing 59% (dry matter basis) of either CCS or BMCS. Feces and urine were collected from each cow and mixed with residual sludge obtained from a manure storage structure. Manure was incubated for 17 wk at 20°C under anaerobic conditions (O2-free N2) in 500-mL glass bottles. Methane emissions and changes in chemical composition of the manure were monitored during the incubation period. The total amount of feces and urine excreted was higher for cows fed BMCS than for cows fed CCS [8.6 vs. 6.5 kg/d of volatile solids (VS)]. Manure from cows fed BMCS emitted more CH4 than manure from cows fed CCS (173 vs. 146 L/kg of VS) throughout the incubation period. Similarly, VS and neutral detergent fiber losses throughout incubation were higher for manure from cows fed BMCS versus cows fed CCS (37.6 vs. 30.6% and 46.2 vs. 31.2%, respectively). Manure NH3 concentration (79% of total manure N) was not affected by corn silage cultivar. Results of this study show that using a more digestible corn silage cultivar (BMCS vs. CCS) may increase the contribution of manure to CH4 emissions, and may offset gain achieved by reducing enteric CH4 emissions.

Benchaar, C., & Hassanat, F. (2019). Methane emissions of stored manure from dairy cows fed conventional or brown midrib corn silage. Journal of dairy science.

Are dietary strategies to mitigate enteric methane emission equally effective across dairy cattle, beef cattle, and sheep?

The digestive physiology of ruminants is sufficiently different (e.g., with respect to mean retention time of digesta, digestibility of the feed offered, digestion, and fermentation characteristics) that caution is needed before extrapolating results from one type of ruminant to another. The objectives of the present study were (1) to provide an overview of some essential differences in rumen physiology between dairy cattle, beef cattle, and sheep that are related to methane (CH4) emission; and (2) to evaluate whether dietary strategies to mitigate CH4 emission with various modes of action are equally effective in dairy cattle, beef cattle, and sheep. A literature search was performed using Web of Science and Scopus, and 94 studies were selected from the literature. Per study, the effect size of the dietary strategies was expressed as a proportion (%) of the control level of CH4 emission, as this enabled a comparison across ruminant types. Evaluation of the literature indicated that the effectiveness of forage-related CH4 mitigation strategies, including feeding more highly digestible grass (herbage or silage) or replacing different forage types with corn silage, differs across ruminant types. These strategies are most effective for dairy cattle, are effective for beef cattle to a certain extent, but seem to have minor or no effects in sheep. In general, the effectiveness of other dietary mitigation strategies, including increased concentrate feeding and feed additives (e.g., nitrate), appeared to be similar for dairy cattle, beef cattle, and sheep. We concluded that if the mode of action of a dietary CH4 mitigation strategy is related to ruminant-specific factors, such as feed intake or rumen physiology, the effectiveness of the strategy differs across ruminant types, whereas if the mode of action is associated with methanogenesis-related fermentation pathways, the strategy is effective across ruminant types. Hence, caution is needed when translating effectiveness of dietary CH4 mitigation strategies across different ruminant types or production systems.

van Gastelen, S., Dijkstra, J., & Bannink, A. (2019). Are dietary strategies to mitigate enteric methane emission equally effective across dairy cattle, beef cattle, and sheep?. Journal of dairy science. Vol. 102, Issue 7, p6109–6130

Northward shift of historical methane emission hotspots from the livestock sector in China and assessment of potential mitigation options

China contributes approximately 10% of the total global methane (CH4) emissions from its livestock sector. However, existing inventories of CH4 emissions from the livestock sector involve significant uncertainty, and the reduction potentials and spatially varying efficiencies of different technical options (adding lipid to diets, acidification, composting, anaerobic digestion, and the combination of composting and anaerobic digestion) have not been systematically assessed at the provincial level. Here, we used a bottom-up approach to compile an up-to-date high-resolution CH4 emission inventory for the livestock sector in China using provincial condition-specific emission factors by considering the gross energy intake and the ambient temperature at the provincial level. A 1-km × 1-km gridded map was produced for 2014, and the temporal trends of the CH4 emissions from 1978 to 2013 were re-visited. The effects of the technical mitigation options that could have been used on CH4 emissions were further evaluated in five different scenarios. Livestock sector CH4 emissions decreased by 1.2 Tg CH4 per year from the period of 1999–2006 to the period of 2007–2014, and this rate was approximately 17–28% lower than previous estimates. During the period of 1978–2014, spatial-temporal emission trends indicated a possible relationship between the Chinese government policies and emissions to some extent and a northward shift of emission hotspots induced by economic and policy incentives. Hotspots with high mitigation potential and efficiency (the achieved reduction under a specific mitigation scenario divided by the baseline emissions from the species affected by the respective technical option) were also identified. The combination of composting and anaerobic digestion is a recommended policy, which can simultaneously address slurry and solid manure and significantly mitigated of CH4 emissions. Overall, this study provides insights into the region-dependent implementation of technical options used to reduce CH4 emissions from the livestock sector in China.

Xu, P., Liao, Y., Zheng, Y., Zhao, C., Zhang, X., Zheng, Z., & Luan, S. (2019). Northward shift of historical methane emission hotspots from the livestock sector in China and assessment of potential mitigation options. Agricultural and Forest Meteorology, 272, 1-11.

Non-CO2 emission from cropland based agricultural activities in India: A decomposition analysis and policy link

Cropland–based agricultural activities emit 34.13% of the total non-carbon dioxide emission in India as of 2007 and contribute 63% of the gross value added from agriculture as of 2014–15. It accounts for 24.17% of the India's total methane and 95.84% of the total nitrous oxide emission from agricultural sector. This article analyzes the change in non-carbon dioxide greenhouse gases emission overtime from India's cropland based agricultural activities for the period of 1980–81 to 2014–15 and uses Logarithmic Mean Divisia Index to identify the factors that are driving this emission change. Results show that during the study period methane emission from paddy cultivation declines at statistically insignificant rate of 200 tonnes per year whereas nitrous oxide emission from nitrogen-fertilizer use increases by approximately 358%, growing at a statistically significant rate of 5100 tonnes per year. Fertilizer intensity contributes 48% in the growth of non-carbon dioxide greenhouse gases emission from cropland based agricultural activities followed by affluence and population growth. On the contrary structural change of the economy with declining relative contribution of agriculture in national gross domestic product, improved productivity of fertilizer use, declining cultivated land per unit of agricultural output and declining emission intensity are helping to reduce emission. Empirical analysis clearly show link between fertilizer policy intervention and nitrous oxide emissions indicating role of policy as an important driver in managing non-carbon dioxide emission from India's cropland–based agricultural activities.

Some, S., Roy, J., & Ghose, A. (2019). Non-CO2 emission from cropland based agricultural activities in India: A decomposition analysis and policy link. Journal of Cleaner Production, 225, 637-646.

Transportation

Description: This section includes articles primarily addressing SLCP measures and innovations related to the Diesel initiative and SLCP emissions in relevant sectors

Natural gas as a ship fuel: Assessment of greenhouse gas and air pollutant reduction potential

Shipping is a significant contributor to global greenhouse gas (GHG) and air pollutant emissions. This study uses a life cycle assessment to compare emissions from domestic and imported liquefied natural gas (LNG), and heavy-fuel oil (HFO) for marine shipping. The findings show that only high-pressure dual-fuel (HPDF) engines robustly reduce well-to-wake GHG emissions by 10% compared with their HFO-fuelled counterparts. This engine technology is only available for large low-speed engines used in ocean-going vessels (OGVs). For smaller vessels, such as ferries, the current deployment of medium speed low-pressure dual-fuel (MS-LPDF) and lean burn spark ignition (LBSI) gas engines cannot reliably reduce GHG emissions. This is primarily due to the high levels of methane slip from these engines. For air pollution reduction, gas engines are found to be an effective means of reducing nitrogen oxides, sulphur oxides and, particulate matter without any additional engine aftertreatment. The HPDF engines, however, need aftertreatment or exhaust gas recirculation to meet the International Maritime Organization Tier III regulations. Sulphur controls, such as the 2020 act, move to limit sulphur to 0.5% globally. However, this will increase the cost of the HFO used by most OGVs, enhancing the economic case for natural gas fuel.

Sharafian, A., Blomerus, P., & Mérida, W. (2019). Natural gas as a ship fuel: Assessment of greenhouse gas and air pollutant reduction potential. Energy Policy, 131, 332-346.

Ship Emission Impacts on Air Quality and Human Health in the Pearl River Delta (PRD) Region, China, in 2015, With Projections to 2030

Ship emissions contribute to air pollution, increasing the adverse health impacts on people living in coastal cities. We estimated the impacts caused by ship emissions, both on air quality and human health, in 2015 and future (2030) within the Pearl River Delta (PRD) region of China. In addition, we assessed the potential health benefits of implementing an Emission Control Area (ECA) in the region by predicting avoided premature mortality with and without an ECA. In 2015, ship emissions increased PM2.5 concentrations and O3 mixing ratios by 1.4 μg/m3 and 1.9 ppb, respectively, within the PRD region. This resulted in 466 and 346 excess premature acute deaths from PM2.5 and O3, respectively. Premature mortality from chronic exposures was even more significant, with 2,085 and 852 premature deaths from ship-related PM2.5 and O3, respectively. In 2030, we projected the future ship emissions with and without an ECA, using two possible land scenarios. With an ECA, we predicted 76% reductions in SO2 and 13% reductions in NOx from the shipping sector. Assuming constant land emissions from 2015 in 2030 (2030 Constant scenario), we found that an ECA could avoid 811 PM2.5-related and 108 O3-related deaths from chronic exposures. Using 2030 Projected scenario for land emissions, we found that an ECA would avoid 1,194 PM2.5-related and 160 O3-related premature deaths in 2030. In both scenarios, implementing an ECA resulted in 30% fewer PM2.5-related premature deaths and 10% fewer O3-related premature deaths, illustrating the importance of reducing ship emissions.

Chen, C., Saikawa, E., Comer, B., Mao, X., & Rutherford, D. Ship Emission Impacts on Air Quality and Human Health in the Pearl River Delta (PRD) Region, China in 2015, with Projections to 2030. GeoHealth.

Real-time particulate emissions rates from active and passive heavy-duty diesel particulate filter regeneration

Periodic regeneration is required to clean the diesel particulate filter (DPF) of heavy-duty diesel vehicle. In this study we analyze real-time particulate matter (PM) mass, particle number, and black carbon emissions during steady state driving active and passive diesel particulate filter (DPF) regenerations on a heavy-duty chassis dynamometer. Regeneration PM emissions were dominated by particles with count median diameter < 100 nm, with the majority <50 nm. Results indicate that vehicle activity during DPF loading significantly affects regeneration particulate emissions. Average PM emission rates (g PM/h) from the 2010 MY vehicle were higher than the 2007 MY vehicle during all regeneration conditions in this study. Sequential forced-active regenerations resulted in reduced particulate mass emissions, but not in reduced particle number emissions, suggesting

incomplete stored PM removal or effects of after-treatment fuel injection. Black carbon emission factors (EFBC) were 3.4 and 21 times larger during driving-active regeneration than during a 50 mph steady state cruise with a recently regenerated DPF for the 2007 and 2010 MY vehicle, respectively. Real-time PM emissions rates were lower during passive regeneration of the 2010 MY DPF, suggesting more modern passive regeneration technologies reduce total on-road particulate and ultrafine particulate emissions.

Smith, J. D., Ruehl, C., Burnitzki, M., Sobieralski, W., Ianni, R., Quiros, D., ... & Dwyer, H. (2019). Real-time particulate emissions rates from active and passive heavy-duty diesel particulate filter regeneration. Science of The Total Environment, 680, 132-139.

Spatial variation in the association between NO2 concentrations and shipping emissions in the Red Sea

Air pollution from shipping emissions poses significant health and environmental risks, particularly in the coastal regions. For the first time, this region as one of the busiest seas and most important international shipping lane in the world with significant nitrogen dioxide (NO2) emissions has been analyzed comprehensively. This paper aims to characterize and quantify the contribution of maritime transport sector emissions to NO2 concentrations in the Red Sea using local Geographically Weighted Regression (GWR) model in a geographic information system (GIS) environment. Maritime traffic volume was estimated using SaudiSat satellite-based Automatic Identification System (S-AIS) data, and the remotely measured tropospheric NO2 concentrations data was acquired from the ozone monitoring instrument (OMI) satellite. A significant spatial variation in the NO2 values was detected across the Red Sea, with values ranging from 4.03 × 1014 to 41.39 × 1014 molecules/cm2. Most notably, the NO2 concentrations in international waters were more than double those in the western coastal regions, whereas the concentrations close to seaports were 100% higher than those over international waters. The results indicated that the local GWR model performed significantly better than the global ordinary least squares (OLS) regression model. The GWR model had a strong and significant overall coefficient of determination with an r2 of 0.94 ($p < 0.005$) in comparison to the OLS model with an r2 of 0.45 ($p < 0.005$). Maritime traffic volume and proximity to seaports weighted by shipping activities explained about 94% of the variations of NO2 concentrations in the Red Sea. The results of this study suggest that the S-AIS data and environmental satellite measurements can be used to assess the impacts of NO2 concentrations from shipping emissions. These findings should stimulate further research into using additional covariates to explain the NO2 concentrations in areas near seaports where the standardized residuals are high.

Alahmadi, S., Al-Ahmadi, K., & Almeshari, M. (2019). Spatial variation in the association between NO2 concentrations and shipping emissions in the Red Sea. Science of The Total Environment, 676, 131-143.

Air quality changes after Hong Kong shipping emission policy: An accountability study

On July 1st, 2015, Hong Kong became the first city in Asia to implement a policy regulating sulfur dioxide (SO2) in shipping emissions. We conducted an accountability study assessing the improvement in ambient air quality and estimating the effect on health outcomes of the policy.

We used interrupted time series (ITS) with segmented regression to identify any change in ambient concentrations of SO2 in contrast to other ambient pollutants (particulate matter <10 µm in diameter (PM10), nitrogen dioxide (NO2) and ozone (O3)) at 10 monitoring stations in Hong Kong from 2010 to 2017. We validated these findings using cumulative sum control (CUSUM) charts. We used a validated risk assessment model to estimate effects of changes in air quality on death for natural causes, cardiovascular and respiratory diseases.

Mean monthly concentrations of SO2 fell abruptly at the monitoring station closest to the main shipping port (Kwai Chung (KC)) by −10.0 µgm3 p-value = 0.0004, but not elsewhere. No such changes were evident for the other pollutants (PM10, NO2, O3). CUSUM charts confirmed a change in July 2015. Estimated deaths avoided per year as a result of the policy were 379, 72, 30 for all natural causes, respiratory and cardiovascular diseases respectively.

Implementation of the shipping emission policy in Hong Kong successfully reduced ambient SO2, with the potential to reduce mortality. However, to gain full benefits, restrictions on shipping emissions need to be implemented throughout the region.

Mason, T. G., Chan, K. P., Schooling, C. M., Sun, S., Yang, A., Yang, Y., ... & Tian, L. (2019). Air quality changes after Hong Kong shipping emission policy: An accountability study. Chemosphere, 226, 616-624.

Air pollution & Health Impacts

Description: This section includes articles primarily addressing linkages between air pollution exposure and health impacts

Changes in the acute response of respiratory diseases to PM2.5 in New York State from 2005 to 2016

Prior studies reported that exposure to increased concentrations of fine particulate matter (PM2.5) were associated with increased rates of hospitalization and emergency department (ED) visits for asthma and chronic obstructive pulmonary disease (COPD). In this study, rates were examined from 2005 to 2016 using a case-crossover design to ascertain if there have been changes in the rates per unit mass exposure given substantial reductions in PM2.5 concentration and changes in its composition. PM2.5 concentrations were reduced through a combination of policies designed to improve air quality and economic drivers, including the 2008 economic recession and shifts in the relative costs of coal and natural gas. The study period was split into three periods reflecting that much of the emissions changes occurred between 2008 and 2013. Thus, the three periods were defined as: BEFORE (2005 to 2007), DURING (2008–2013), and AFTER (2014–2016). In general, the number of hospitalizations and ED visits declined with the decreased concentration of PM2.5. However, the rate of COPD hospitalizations and asthma ED visits associated with each interquartile range increase in ambient PM2.5 concentration was larger in the AFTER period than the DURING and BEFORE periods. For example, each 6.8 μg/m3 increase in PM2.5 on the same day was associated with 0.4% (0.0%, 0.8%), 0.3% (−0.2%, 0.7%), and 2.7% (1.9%, 3.5) increases in the rate of asthma emergency department visits in the BEFORE, DURING, and AFTER periods, respectively, suggesting the same mass concentration of PM2.5 was more toxic in the AFTER period.

Hopke, P. K., Croft, D., Zhang, W., Lin, S., Masiol, M., Squizzato, S., ... & Rich, D. Q. (2019). Changes in the acute response of respiratory diseases to PM2. 5 in New York State from 2005 to 2016. Science of The Total Environment, 677, 328-339.

Long-term health impact assessment of total PM2.5 in Europe during the 1990–2015 period

Several datasets of PM2.5 concentrations over Europe during the 1990–2015 period, were used to calculate health impacts from chronic exposure to total particle matter below 2.5 μm (i.e. PM2.5). The datasets used in the analysis include the European Topic Centre on Air Pollution and Climate Change Mitigation (ETC/ACM), the Copernicus Atmospheric Monitoring Service (CAMS), the Global Burden of Disease (GBD), the World Health Organization (WHO) as well as the EURODELTA-Trends (EDT) multi-model reanalysis developed specifically for Europe.

The exposure to ambient PM2.5 concentrations was calculated as population weighted annual average PM2.5 concentrations by country. The calculated exposure to PM2.5 was later used as input in the health impact assessment (HIA) Alpha-RiskPoll (ARP) tool to retrieve the total number of premature deaths.

Our results indicate a substantial reduction in the number of premature deaths from PM2.5 exposure in Europe over the 1990–2010 period, between nearly 30 and 50%. Putting all the data-sets together, even if they do not cover the whole period, a decrease of even around 60% is observed between 1990 and 2015. For the countries included in this study, the estimated number of premature deaths from PM2.5 in 1990 was found to be around 960 000 (median of all the available datasets), whereas in 2015 it was found to be around 445 000. However, the variability in the estimated premature deaths from the different PM2.5 datasets was found to be large during the early 90s (around a factor of 2). For the latest years of the investigated period (2005 onwards), where a relatively flat trend in the PM2.5 exposure was observed, the differences between the different datasets were smaller.

Even though our results indicate a reduction in the number of premature deaths from chronic exposure to PM2.5,

the numbers remain considerable in 2015, underlining the need to continue improving air quality in the future.

Ciarelli, G., Colette, A., Schucht, S., Beekmann, M., Andersson, C., Manders-Groot, A., ... & Adani, M. (2019). Long-term health impact assessment of total PM2. 5 in Europe during the 1990–2015 period. Atmospheric Environment: X, 3, 100032.

Particulate matter-attributable mortality and relationships with carbon dioxide in 250 urban areas worldwide

Urban air pollution is high on global health and sustainability agendas, but information is limited on associated city-level disease burdens. We estimated fine particulate matter (PM2.5) mortality in the 250 most populous cities worldwide using PM2.5 concentrations, population, disease rates, and concentration-response relationships from the Global Burden of Disease 2016 Study. Only 8% of these cities had population-weighted mean concentrations below the World Health Organization guideline for annual average PM2.5. City-level PM2.5-attributable mortality rates ranged from 13–125 deaths per 100,000 people. PM2.5 mortality rates and carbon dioxide (CO2) emission rates were weakly positively correlated, with regional influences apparent from clustering of cities within each region. Across 82 cities globally, PM2.5 concentrations and mortality rates were negatively associated with city gross domestic product (GDP) per capita, but we found no relationship between GDP per capita and CO2 emissions rates. While results provide only a cross-sectional snapshot of cities worldwide, they point to opportunities for cities to realize climate, air quality, and health co-benefits through low-carbon development. Future work should examine drivers of the relationships (e.g. development stage, fuel mix for electricity generation and transportation, sector-specific PM2.5 and CO2 emissions) uncovered here and explore uncertainties to test the robustness of our conclusions.

Anenberg, S. C., Achakulwisut, P., Brauer, M., Moran, D., Apte, J. S., & Henze, D. K. (2019). Particulate matter-attributable mortality and relationships with carbon dioxide in 250 urban areas worldwide. Scientific reports, 9(1), 1-6.

PM2.5 and Air Pollution

Description: This section includes articles addressing PM2.5 and air pollution source apportionment, impacts and emissions trends.

Impacts of air pollutants from rural Chinese households under the rapid residential energy transition

Rural residential energy consumption in China is experiencing a rapid transition towards clean energy, nevertheless, solid fuel combustion remains an important emission source. Here we quantitatively evaluate the contribution of rural residential emissions to PM2.5 (particulate matter with an aerodynamic diameter less than 2.5 μm) and the impacts on health and climate. The clean energy transitions result in remarkable reductions in the contributions to ambient PM2.5, avoiding 130,000 (90,000–160,000) premature deaths associated with PM2.5 exposure. The climate forcing associated with this sector declines from 0.057 ± 0.016 W/m2 in 1992 to 0.031 ± 0.008 W/m2 in 2012. Despite this, the large remaining quantities of solid fuels still contributed 14 ± 10 μg/m3 to population-weighted PM2.5 in 2012, which comprises 21 ± 14% of the overall population-weighted PM2.5 from all sources. Rural residential emis- sions affect not only rural but urban air quality, and the impacts are highly seasonal and location dependent.

Shen, G., Ru, M., Du, W., Zhu, X., Zhong, Q., Chen, Y., ... & Cheng, H. (2019). Impacts of air pollutants from rural Chinese households under the rapid residential energy transition. Nature communications, 10.

Establishment of county-level emission inventory for industrial NMVOCs in China and spatial-temporal characteristics for 2010–2016

Volatile organic compounds (VOCs) pollution, which is closely linked to photochemical smog and secondary organic aerosols, has become a severe concern in China. Therefore, we compiled a new high-resolution emission inventory for the industrial non-methane Volatile organic compounds (NMVOCs) using "bottom-up" approaches throughout 2010 and 2016. In this work, the industrial sources were divided into five major categories, and 108 specific sources, as well as an emission factor database, was developed for industrial NMVOCs. Results indicated that the total NMVOCs emissions from industrial sources increased from 16.88 Tg in 2010 to 21.04 Tg in 2016 at an annual average rate of 3.7%. The five major source categories including "production of VOCs", "storage and transportation", "industrial processes using VOCs as raw material", "processes using VOCs-containing products", and "fossil fuel combustion" generated 1.92 Tg, 0.94 Tg, 6.54 Tg, 10.04 Tg, and 1.60 Tg NMVOCs, respectively, in 2016. Coke production, plastic manufacturing, raw medicine industry, and architectural decoration were the primary sources of industrial NMVOCs and emissions of these sources increased by 140 Gg, 190 Gg, 640 Gg, and 700 Gg between 2010 and 2016. The emissions displayed distinct spatial characteristics, with significantly higher emissions in the Beijing-Tianjin-Hebei region, the Pearl River Delta, the Yangtze River Delta, and the Cheng-Yu region than in other areas. Shandong, Guangdong, Jiangsu, Zhejiang, and Henan were the top five provinces with the highest NMVOCs emissions, while the emission hotspots in the county-level were mainly distributed in Guangzhou urban area, Shanghai Pudong New Area, Hangzhou urban area, and Shenzhen urban area. The emissions in Henan province, Hubei province, and Cheng-Yu region increased significantly during the study period. Instead, emissions in some counties of Zhejiang province and Hebei province decreased than in 2010.

Simayi, M., Hao, Y., Li, J., Wu, R., Shi, Y., Xi, Z., ... & Xie, S. (2019). Establishment of county-level emission inventory for industrial NMVOCs in China and spatial-temporal characteristics for 2010–2016. Atmospheric Environment, 211, 194-203.

National air pollution distribution in China and related geographic, gaseous pollutant, and socio-economic factors

Regional specification of PM2.5 pollution characteristics is crucial for pollution control and policymaking. Spatiotemporal variations of six criteria air pollutants and influencing factors in China were studied using hourly concentrations of PM2.5, PM10, SO2, NO2, CO, and O3 from 2015 to 2016. China was categorized into eight regions: north-east, northern coastland, eastern coastland, southern coastland, Yellow River middle reaches, Yangtze River middle reaches, south-west, and north-west. The 29 exemplary cities in China were also researched. It was found that the PM2.5 concentration in the northern coastland (Beijing–Tianjin–Hebei–Shandong) was the highest (72.28 μg.m−3) among the eight regions, particularly in the city of Baoding, Hebei, which had an annual average PM2.5 concentration of 98.53 μg.m−3. Average PM2.5 concentrations in 2015 and 2016 of China were 50.16 μg.m−3 and 46.61 μg.m−3, respectively. Compared with 2015, the PM2.5 concentration decreased by 8.41% in 2016, the decline of PM2.5 in summer was the largest, followed by autumn, spring and winter. The average mean PM2.5 concentrations of the 29 exemplary cities in 2015 and 2016 were 54.66 μg.m−3 and 48.37 μg.m−3, respectively, exceeding the limit for grade 2 of the national standards (35 μg.m−3). National air pollution distribution has exploded geographically with influence of regional economic factors. Gaseous pollutant as well as geographical and socio-economic conditions influenced PM2.5 emissions. Effects of these factors on PM2.5 emissions varied across regions and decreased continuously from the northern region to the south-west and eastern coastland regions. This paper clearly identifies the regional characteristics and distribution of PM2.5, focusing on the effects of gaseous pollutant, geography and socio-economic development. Secondary transformation and vehicle exhaust across regions should be further studied.

Liang, D., Wang, Y. Q., Wang, Y. J., & Ma, C. (2019). National air pollution distribution in China and related geographic, gaseous pollutant, and socio-economic factors. Environmental Pollution, 250, 998-1009.

Estimation of losses in solar energy production from air pollution in China since 1960 using surface radiation data

China is the largest worldwide consumer of solar photovoltaic (PV) electricity, with 130 GW of installed capacity as of 2017. China's PV capacity is expected to reach at least 400 GW by 2030, to provide 10% of its primary energy. However, anthropogenic aerosol emissions and changes in cloud cover affect solar radiation in China. Here, we use observational radiation data from 119 stations across China to show that the PV potential decreased on average by 11–15% between 1960 and 2015. The relationship between observed surface radiation and emissions of sulfur dioxide and black carbon suggests that strict air pollution control measures, combined with reduced fossil fuel consumption, would allow surface radiation to increase. We find that reverting back to 1960s radiation levels in China could yield a 12–13% increase in electricity generation, equivalent to an additional 14 TWh produced with 2016 PV capacities, and 51–74 TWh with the expected 2030 capacities. The corresponding economic benefits could amount to US$1.9 billion in 2016 and US$4.6–6.7 billion in 2030.

Sweerts, B., Pfenninger, S., Yang, S., Folini, D., Van der Zwaan, B., & Wild, M. (2019). Estimation of losses in solar energy production from air pollution in China since 1960 using surface radiation data. Nature Energy, 4(8), 657-663.

No one knows which city has the highest concentration of fine particulate matter

Exposure to ambient fine particulate matter (PM2.5) is the leading global environmental risk factor for mortality and disease burden, with associated annual global welfare costs of trillions of dollars. Examined within is the ability of current data to answer a basic question about PM2.5, namely the location of the city with the highest PM2.5 concentration. The ability to answer this basic question serves as an indicator of scientific progress to assess global human exposure to air pollution and as an important component of efforts to reduce its impacts. Despite the importance of PM2.5, we find that insufficient monitoring data exist to answer this basic question about the spatial pattern of PM2.5 at the global scale. Only 24 of 234 countries have more than 3 monitors per million inhabitants, while density is an order of magnitude lower in the vast majority of the world's countries, with 141 having no regular PM2.5 monitoring at all. The global mean population distance to nearest PM2.5 monitor is 220 km, too large for exposure assessment. Efforts to fill in monitoring gaps with estimates from satellite remote sensing, chemical transport modeling, and statistical models have biases at individual monitor locations that can exceed 50 μg m−3. Progress in advancing knowledge about the global distribution of PM2.5 will require a harmonized network that integrates different types of monitoring equipment (regulatory networks, low-cost monitors, satellite remote sensing, and research-grade instrumentation) with atmospheric and statistical models. Realization of such an integrated framework will facilitate accurate identification of the location of the city with the highest PM2.5 concentration and play a key role in tracking the progress of efforts to reduce the global impacts of air pollution.

Martin, R. V., Brauer, M., van Donkelaar, A., Shaddick, G., Narain, U., & Dey, S. (2019). No one knows which city has the highest concentration of fine particulate matter. Atmospheric Environment: X, 100040.

SLCPs & Vulnerable Regions

Description: This section includes articles addressing SLCP impacts on vulnerable regions or studies discussing the specific vulnerabilities of regions to SLCPs.

Investigation of potential source regions of atmospheric Black Carbon in the data deficit region of the western Himalayas and its foothills

In the present study, BC was measured at three western Himalayan sites (Site-A ≈ 650 m, Site-B ≈ 2050m and Site-C ≈ 2600 m a.s.l.) during summer and winter seasons of 2014–2016. The objective of this study is to investigate the variability of BC as a function of meteorological conditions and identify potential combustion sources (biomass vs fossil fuel). Furthermore, boundary layer (ABL) height and wind patterns, MODIS fire maps

and Concentrated Weightage Trajectory (CWT) analysis were utilized to study potential BC source regions. The average BC concentration at Site-A, B and C were observed to be 4.98 ± 2.79, 4.57 ± 3.54 and 3.01 ± 2.95 µgm−3, respectively. At Site-B, daytime BC was observed to be higher than nighttime, indicating that ABL development and consequent upward transport of pollution from IGP contributed to high BC concentrations in lesser Himalayas. Nevertheless, variable fraction of BC attributable to biomass vs fossil fuel at three stations indicates the effect of transport from IGP overlapped with the effect of mixing with different combustion sources, including local biomass burning practices which modulated BC levels especially at a high-altitude site in winter. On the basis of CWT analysis and MODIS fire counts, emissions from agriculture residue burning in northwestern-IGP impacted the BC aerosols at all monitoring locations, although, based on our in-situ aethalometer measurements, biomass burning fraction of BC remained below 25–30% at Site-A and B. Episodic westerly long-range transport events (from Middle-East, Europe and Central-Asia) can contribute to background BC concentrations especially in wintertime which were, however, in range of sub-µgm−3 levels based on our observations at Site-C.

Soni, A., Decesari, S., Shridhar, V., Prabhu, V., Panwar, P., & Marinoni, A. (2019). Investigation of potential source regions of atmospheric Black Carbon in the data deficit region of the western Himalayas and its foothills. Atmospheric Pollution Research.

The cascade of global trade to large climate forcing over the Tibetan Plateau glaciers

Black carbon (BC) aerosols constitute unique and important anthropogenic climate forcers that potentially accelerate the retreat of glaciers over the Himalayas and Tibetan Plateau (HTP). Here we show that a large amount of BC emissions produced in India and China—a region of BC emissions to which the HTP is more vulnerable compared with other regions—are related to the consumption of goods and services in the USA and Europe through international trade. These processes lead to a virtual transport pathway of BC from distant regions to the HTP glaciers. From a consumption perspective, the contribution from India to the HTP glaciers shows a rapid increasing trend while the contributions from the USA, Europe, and China decreased over the last decade. International trade aggravates the BC pollution over the HTP glaciers and may cause significant climate change there. Global efforts toward reducing the cascading of BC emissions to Asia, especially the Indian subcontinent, are urgently needed.

Yi, K., Meng, J., Yang, H., He, C., Henze, D. K., Liu, J., ... & Cheng, Y. (2019). The cascade of global trade to large climate forcing over the Tibetan Plateau glaciers. Nature communications, 10(1), 3281.