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Research article

Transboundary air pollution from coal-fired power generation

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ABSTRACT

To what extent do the short-term negative externalities of fossil fuel use traverse national borders? Transnational negative externalities are thought to motivate international environmental cooperation, but we often lack detailed data on their occurrence. Using a Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT), we offer global estimates of the extent of transboundary air pollution from coal-fired power generation. In an advance of the existing literature, we attribute the air pollution experienced in different locales to specific coal-fired power plants, allowing us to evaluate the extent to which pollution from the coal industry is experienced across different jurisdictions. Our results indicate that the issue is most severe in South Asia and East Asia. When weighting by the population of "receiving" locations, India is found to be the largest emitter of transboundary air pollution, followed by China. Residents of Bangladesh are found to experience the most transboundary air pollution by a wide margin.

1. Introduction

Transboundary negative externalities, from greenhouse gas emissions to air and water pollution, play an important role in global environmental politics (Barrett, 1990). They allow states to "pass off" the polluting byproducts of industrial activity, forcing other governments to adapt to environmental degradation not of their own doing. International environmental agreements aim to generate mutual gains from cooperation between sovereign governments on negative externalities that cross national borders (e.g., Barrett, 2003). In these agreements, governments agree to control their pollution or resource use such that each party reaps net gains. Even though each government incurs a cost from mitigating the problem, the agreement is worthwhile if collective gains from a cleaner environment are large enough and the terms of cooperation enforceable. In political science, theoretical work on the complications stemming from negative externalities is well developed. But empirical research on its extent, incidence, and consequence remains limited. In some cases, such as global warming and ozone depletion, the externalities are truly global and the geographic location of a source is irrelevant. But in others, such as for air pollution, the location of the source determines where the negative externality is experienced. In the case of coal, communities proximate to or "down wind" from power plants disproportionately bear the costs of these externalities. Understanding the incidence of air pollution is valuable both academically, as it outlines the domains in which international environmental cooperation would be useful, and for policy, as it helps governments identify these opportunities for welfare-enhancing cooperation.

These externalities have attracted particular attention in work on global warming. Because the environmental consequences of fossil fuel combustion are widely dispersed, markets fail to accurately price fossil fuel-intensive activities, leading to excessive greenhouse gas emissions. For this reason, Stern (2007) terms anthropogenic climate change "the greatest and widest-ranging market failure ever seen". Yet international efforts to mitigate climate change have stagnated, partly because the effects of greenhouse gas emissions take long periods of time to become apparent (Hovi et al., 2009). As some authors have pointed out, however, a short-term co-benefit of mitigation—improved air quality—may lead to the adoption of stronger climate policies (Keohane and Victor, 2016). Frustration with poor air quality may lead to publics placing pressure on governments to better limit pollution (Alkon and Wang, 2018). Should the consequences for air quality of fossil fuel combustion cross borders, it may provide an impetus for a renewal of international climate-relevant cooperation.

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Existing work offers limited information on the extent to which these consequences actually do cross borders. Though research has been done on the occurrence of transboundary pollution in particular regions (e.g., de Leeuw, 2002; Kaldellis et al., 2007), we lack information on its occurrence globally. To rectify this, we contribute in this paper new estimates of the extent and trajectory of transboundary air pollution from coal-fired power generation. Coal is a leading power source throughout the world and a major contributor to greenhouse gas emissions (IEA, 2017; Myhrvold and Caldeira, 2012). It is also known to generate a number of short-term environmental externalities that contribute to higher mortality rates and increased occurrences of other maladies (Chen et al., 2013; Huang et al., 2012). We use the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess, 1998) to describe the dispersion of air pollutants from all coal-fired power plants in the world, weighted by the size of the emitting plant, the plant's sulfur dioxide (SO_2) emissions, and the population of the locality experiencing the airborne pollutants.

We find that transboundary air pollution from coal-fired power generation is a global problem, but one that is most severe in South Asia and East Asia, areas of both heavy reliance on coal and high levels of population density. China and India are the two largest emitters of transboundary air pollution when accounting for the population in "receiving" areas, while the population of Bangladesh suffers the most from pollutants emitted abroad.

While scholars have examined issues of local and transboundary pollution, this paper is one of the first to precisely estimate transboundary pollution flows attributable to specific sources (individual coal-fired power plants). In doing so, this paper provides new information on the extent and magnitude of transboundary air pollution, enabling researchers to explore topics including the effect of incoming transboundary pollution on attitudes towards the environment and the political determinants of variation across country dyads in the extent of cross-border pollution flows. It further provides information on the degree to which the short-term co-benefits of climate change mitigation, such as improved air quality, would be shared across countries.

2. Transboundary negative externalities in international relations

In international relations, negative transboundary externalities are produced when activities in one country impose unintended costs on other countries. This is a particularly salient issue in the domain of environmental politics, where water or air pollution produced by industrial activity in one country can easily traverse national borders (e.g., Cao and Prakash, 2010). Theoretically, transboundary externalities in this context both require greater international cooperation, as the recipients of transboundary pollution cannot address these externalities unilaterally, and make cooperation more difficult, as the producer of the externalities does not bear their costs and hence lacks a strong motivation to mitigate (Sigman, 2002). Air pollution in fact is an example of an externality given by Coase (1960) and reiterated by Keohane (1984) as a problem that belies easy resolution in world politics, at least in the absence of a well-established international organization.

Work has been done on how countries can overcome these difficulties to address transboundary externalities. Sprinz and Vaahtoranta (1994) detail, for example, the negotiations leading to the 1985 Helsinki Protocol on transboundary acid rain in Europe, while Mitchell (1994) considers the institutional design rules that create disincentives to the production of pollutive externalities. Additionally, substantial work has been done on how international trade might produce transboundary pollution, and how said transboundary water and air pollution might impede gains from trade (e.g., Benarroch and Thille, 2001; Cao and Prakash, 2010; Conconi, 2003). But less is known about the specific origins of transboundary air pollution and its political, social, and economic effects. Bernauer and Koubi (2009) link democratic forms of government to improved air quality, drawing on the traditional claim that democracies are particularly adept at providing public goods (Bueno de Mesquita et al., 2003). Bernauer and Kuhn (2010) extend this to the transnational case, examining upstream-downstream water pollution in Europe. Notably, they find that while democracy induces cleaner economic activity at home, it does not have a large effect on transboundary air pollution—incentives for upstream polluters to free ride on downstream countries remain strong even among wealthy democracies. Perrin and Bernauer (2010) find similar results in the context of the Convention on Long-Range Transboundary Air Pollution: net exporters of pollution were substantially less likely to ratify than net receivers, suggesting again the presence of strong free-riding incentives.

Transboundary air pollution from coal, the focus of this study, may be a particularly difficult issue to resolve. Coal-fired power generation is closely linked to economic growth in many developing countries, where there are also significant issues of corruption and weak oversight. Recent electrification drives in China, for example, have been driven by increased reliance on coal-fired power generation (Wolfram et al., 2012). On the latter point, Cole (2007) ties higher levels of corruption to more domestic air pollution, in part through an undermining of environmental regulations and enforcement. In India, which is one of the world's largest consumers of coal, enforcement of environmental standards on industrial plants is often weak and plagued by corruption (Duflo et al., 2013). The implication is that free-riding incentives may be particularly strong in the case of transboundary air pollution from coal in developing countries, where coal is seen as important to fueling economic growth and where enforcement of pollution standards is often lax.

Issues of air pollution from coal combustion speak to more general problems of mitigating climate change. Climate change has been described as a "problem of externalities ... on steroids", due to the centrality of transboundary externality issues and concomitant free-riding incentives (Greenstone and Jack, 2015, 33). Whereas certain pollutants may only affect relatively limited geographic areas, central to climate change are "uniformly mixed" pollutants that do damage around the world, regardless of their initial location.

Coal combustion produces severe localized pollution (e.g., Ebenstein et al., 2017) and, through the emission of greenhouse gases, is a key driver of the global greenhouse effect. Transitioning away from coal is seen as necessary for climate change to be successfully mitigated (Myhrvold and Caldeira, 2012). This paper probes the precise extent to which pollutants released from coal combustion travel geographically and are experienced by foreign populations. By focusing on transboundary air pollution produced by coal combustion, we offer insights into how the unique politics around coal power and broader issues of negative transboundary externalities interact, speaking to questions around the determinants of national climate policies and the likelihood of international cooperation on climate change.

This paper additionally offers a substantial methodological contribution. With our use of a HYSPLIT model, grounded in both the location of a given power plant and the prevailing meteorological conditions in its vicinity, we are able to provide high-resolution estimates of the geographic dispersal of pollutants released by specific plants at a global scale. In an advance over existing literature, this permits us to obtain precise estimates of the extent to which the short-term negative externalities of fossil fuel combustion are experienced domestically or passed off onto other jurisdictions.

3. Transboundary air pollution from coal-fired power generation

Coal-fired power generation is a major source of air pollution. It is estimated that in 2010, coal-fired power plants generated 2.51 megatons of $PM_{2.5}$ emissions, accounting for 95% of $PM_{2.5}$ emissions from fossil fuel-powered power units. Coal was also estimated to have produced 77% of SO_2 emissions from fossil fuel-burning power plants, 75% of nitrous oxide emissions, and 73% of carbon dioxide emissions (Tong et al., 2018).

There have been prior academic evaluations of transboundary air pollution. Some scholars have used atmospheric models to simulate trajectories of air mass and demonstrate the extent of transboundary air pollution (e.g., Li et al., 2010; Mallik et al., 2013). Other studies have focused on pollution "shocks" in single locales (e.g., Jeong et al., 2013). Although there is substantial evidence pointing to the occurrence of transboundary air pollution, one persistent challenge has been in attributing air pollution to specific pollution sources. In the context of coal, some researchers have exploited unique characteristics of pollutants released by coal (the metallic content) to link transboundary pollution to coal combustion (e.g., Moreno et al., 2012; Dong et al., 2017). Yet this work often relies on narrow case studies and cannot always pinpoint the exact site of coal combustion. We move beyond this by estimating global flows of pollutants from coal combustion across specific power plants.

4. Research design

We draw our sample of coal-fired power plants from the 2017 edition of the Global Coal Plant Tracker, which contains a global database of coal-fired power plant units with capacities of at least 30 megawatts (MW). We supplement this with information from the Global Energy Observatory and SourceWatch, also from 2017. These data include individual coal plant units' commissioning dates, statuses (i.e., actively operating or not), power generation capacities, and precise coordinate locations, which were verified through several rounds of multi-coder review. The sample contains 6922 coal plant units operating as of 2017 (see plant map in Appendix A1); coordinates are missing for 512 of these units (7.4% of the sample).

Though polluting plants are often placed in areas populated by domestically disadvantaged groups (e.g., Brulle and Pellow, 2006), we lack indications that countries strategically place their plants near international borders to direct pollution abroad. Economic and natural resource constraints are likely of higher priority when building plants. This is supported by previous studies on how siting decisions are actually made (Aguilar et al., 2012; Xie et al., 2016).

4.1. Air pollution models and administrative boundaries

We construct estimates of the likely dispersal of individual particles from each plant in the dataset. A standard number of generic particles is assumed to be emitted by individual plants. To capture the magnitude of air pollution flowing across borders, we multiply sums of particles observed in different countries by a set of weights intended to estimate the severity of pollution emitted by particular plants. These weights, discussed in greater detail below, focus on the capacity of a given plant, the amount of SO_2 it emits, and the size of the population that receives the emitted pollutants.

We estimate a HYSPLIT model based on conditions in 2013 to measure the trajectories of particles emitted from operating plants (Draxler and Hess, 1998). We run forward trajectories for each power plant in our dataset every four days for the entire year of 2013, at four separate times each day (5:00, 11:00, 17:00, 23:00 UTC). We assume that the particles have a four-day lifespan. We run the models assuming the particles are released at an altitude of 100 m. To estimate the movement of the particles, we use meteorological data from the Global Data Assimilation System at a 1° resolution. The sensitivity of our results to alternate parameterizations is discussed in Section 5.2.

The HYSPLIT approach allows us to obtain detailed information on the likely dispersal of pollutants from plants in our sample, thereby enabling us to "attribute" air pollution experienced in particular localities to specific sources. This is a substantial step forward for the social science literature on pollution, which often considers transboundary pollution flows in fairly coarse terms with regard to origin locations. This application of HYSPLIT modeling expands on recent work by Kopas et al. (2020), who use such a technique to evaluate the distribution of domestically generated air pollution in India.

Despite these advantages, there are some limitations to our approach that are worth noting. First, HYSPLIT models require assumptions to be made about the height at which pollutants are released (e.g., the height of coal plant stacks) and the "transmission time" of individual particles, or the length of time for which they are able to travel. In our primary model, we assume constant heights and transmission times across plants. In a robustness check discussed below, we test for the sensitivity of our results to changes in these parametric inputs. We find that our results are largely robust to these alternate specifications.

Second, our model only considers transboundary pollution from primary air pollutants, taking no account of secondary pollutant formation or further chemical reactions between pollutants. While we weight pollution by plants' emissions of SO_2, an important source of aerosol formation (Kasahara and Takahashi, 1976; Stangl et al., 2019), we do not directly model the contribution of aerosol formation to transboundary pollution. The chemical formation of transboundary air pollution can be better addressed with Eulerian chemical transport models (CTMs), but running CTMs for a large number of individual plants is not computationally feasible at this time. Further, pollutant flows estimated via CTMs may be too coarse to attribute to specific plants. Under the Task Force of Hemispheric Transport of Air Pollution (TF-HTAP), a number of CTM studies have been conducted to quantify the source–receptor relationships of ozone and $PM_{2.5}$, but these studies principally quantify the transboundary impacts of total anthropogenic emissions (West et al., 2009).

To estimate the degree to which transboundary air pollution is experienced by foreign populations, we overlay particle trajectory estimates onto high-resolution gridded population data provided by the Center for International Earth Science Information Network (CIESIN, 2017). We use the latest available population data from 2010 at a 2.5-minute grid resolution. In supplementary tests, we scale these cell-level population figures according to the national population of the receiving country, which allows for an assessment of the proportion of a country's population that experiences transnational pollution. Data for these analyses are gathered from the World Bank's World Development Indicators dataset for the year of 2010.

4.2. Country characteristics

To calculate the amount of transboundary air pollution emitted by a particular country, we estimate the amount of pollution released by each coal-fired power plant present within its borders. To do this, we record the number of particles released by a given plant that are "observed" in other countries (excluding particles observed over oceans), as estimated by our HYSPLIT model. We then multiply each particle by weights that capture the full operating capacity of the plant, its SO_2 emissions intensity (ratio of SO_2 emissions to capacity), and the population of the receiving grid cell (using the aforementioned CIESIN data). The assumption here is that the interaction of a plant's nameplate capacity and its SO_2 emissions intensities provides an accurate approximation of the total amount of pollutants released by the plant.

We include the SO_2 intensity weight to capture variation across plants in emissions owing, for example, to different pollution control technologies that may be in place. We gather this SO_2 emissions information from the Global Power Emissions Database (Tong et al., 2018), which includes plant-specific data on SO_2 emissions as of 2010. We link plants in this database to those in our own dataset via a combination of automated and manual matching according to plant name and country. In cases where a match between the two datasets cannot be made, we use country-level averages to approximate a plant's emissions intensity (i.e., the mean ratio of SO_2 emissions to capacity across all coal-fired power plants in a country). Additional details on this weighting process are provided in Appendix A2.

Following this, we sum these weighted values for each coal plant in a given country to calculate the total amount of transboundary pollution emitted by that country. We additionally compare these values to the amount of air pollution from coal-fired power plants that is experienced domestically, which allows for an analysis of the extent to which countries internalize or pass off the pollution costs of industrial coal combustion. On the receiving end, to measure countries' *exposure* to transboundary air pollution, we sum the number of particles emitted by foreign plants observed in a given country, with each particle multiplied by the plant-level capacity, SO_2, and population weights. We further calculate the ratio of transboundary pollution to domestic air pollution from coal-fired plants, which provides an estimate of the degree to which foreign coal combustion is responsible for individuals' experienced air quality relative to domestic coal combustion.

Summary statistics are available in Appendix A3. In Appendices A7 and A8, we test for whether the age of a given plant and the political-economic profile of an emitting country predicts the amount of transboundary pollution released; we find weak associations in both cases.

5. Results

Analysis of estimated transboundary pollution flows reveals heavy right skews to the distributions of pollution emitters and receivers. India, notably, produces far more weighted transboundary air pollution than any other country. It emits roughly 7.6 standard deviations more transboundary pollution than the mean coal-producing country; about four times as much as China, the second-largest emitter of weighted transboundary pollution; and nearly ten times more than Turkey, the third-largest emitter. Among receivers of transboundary pollution, Bangladesh experiences the most transboundary air pollution by a wide margin owing to its proximity to Indian coal plants. Its weighted transboundary pollution load that exceeds that of the mean country by 13 standard deviations and is nearly four times heavier than the pollution load experienced in Pakistan, the second-largest recipient. Transboundary air pollution appears to be most severe in South and East Asia more generally. The United States emits a notable amount of transboundary pollution, primarily received by Canada, as do various European countries. Interestingly, the Nordic countries, which led the push for the 1985 Helsinki Protocol on transboundary pollution (Sprinz and Vaahtoranta, 1994), are estimated to receive relatively low levels of transboundary pollution today. These results are described in Table 1 and depicted graphically in Fig. 1.

We further evaluate pollution flows while adjusting cell-level population figures for national populations. As depicted in Fig. 2, South Africa is the largest emitter of transboundary pollution when accounting for the total size of receiving country populations, principally due to its neighbor Swaziland, which is recorded as by far the largest recipient of transboundary pollution in this alternative weighting scheme.

We additionally calculate the ratio of domestic to foreign and foreign to domestic pollution for each country. As a relatively isolated country, Australia experiences the highest proportion of domestic pollution relative to foreign pollution, followed by Chile. Bangladesh experiences the most foreign pollution relative to domestic pollution, followed by Sweden, Pakistan, and Argentina.

Lists of countries by the ratios of domestic to foreign pollution and foreign to domestic pollution are included in Table 1, along with lists of the largest emitters and recipients and the list of most polluted country dyads. Notably, India or China is the emitter in eight of the ten country dyads in which transboundary air pollution is most severe. Bangladesh and Pakistan are the primary recipients of pollution from India, while Vietnam and South Korea bear the brunt of Chinese pollution. The amount of pollution sent from India to Bangladesh is particularly noteworthy—it exceeds the mean pollution exchanged between a country dyad by 45 standard deviations and is roughly eleven times more severe than pollution emitted across the largest non-India dyad (China to Vietnam). The pollution data used to calculate these rankings include the capacity, SO_2, and population weights described previously (they exclude adjustments for national populations).

Table 2 presents lists of the largest emitters, receivers, and country dyads when adjusting for the national population of a receiving country. As noted above, South Africa is the largest emitter and Swaziland the largest recipient of transboundary pollution when accounting for national population size, though they are immediately followed by India and Bangladesh, respectively. Given that it is one of the most populous countries in the world, the high ranking of Bangladesh in this scheme is striking and further underscores the severity of transboundary pollution experienced in the country.

These findings are summarized in Fig. 3, which depicts total pollution emitted and received by country across both domestic and foreign plants. Without adjusting for national populations, our model estimates that India produces just over 50% more pollution through coal combustion (both domestic and transboundary) than China and over 60 times as much as the United States.

Residents of India additionally *receive* about a third more pollution from coal combustion than people in China. In both India and China, it is notable that a vast majority of the pollution emitted is experienced domestically; relatively little is passed off onto nearby countries. Pollution elsewhere in South and Southeast Asia largely originates abroad, however, particularly in Bangladesh, Pakistan, and Vietnam. This indicates that while emissions of transboundary pollution are comparatively minor in India and China, they are practically significant for other countries in the region.

5.1. Seasonality and sensitivity tests

Results for pollution loads emitted and received use data aggregated by year. However, meteorological conditions shift within years, suggesting that there may be seasonal variation in transboundary pollution flows (Keating et al., 2010). To assess this possibility, we select five plants responsible for emitting large amounts of air pollution and rerun the HYSPLIT model for each of the four seasons in 2013. These include three plants in India (the Kahalgaon Super Thermal Power Plant, Farakka Super Thermal Power Station, and Talwandi Sabo Power Project), as well as one in Vietnam (the Mong Duong power station) and one in Taiwan (the Taichung power station). The results are presented in Appendix A4.

The Kahalgaon Super Thermal Power Plant appears to generate the most transboundary pollution in the winter and spring, a pattern also apparent for the other three Indian plants. Tests for the Taichung power station in Taiwan show different transboundary patterns over the four seasons, however. In winter and fall, air pollutants are more likely to be transported to Vietnam, Cambodia, and elsewhere in Southeast Asia; in the spring, some pollution is diverted to mainland China; in the summer, most pollution heads northward to China and the Korean peninsula. This seasonal variation appears unlikely to significantly affect the general tenor of the our main country-level results, but might be probed in further detail in future work.

As an additional robustness check, we consider the sensitivity of our results to different parameter assumptions, which are required for HYSPLIT models. To assess the severity of these issues, we alter two parameters within the HYSPLIT model: the height of a plant's stack (10 meters and 200 m, versus a default of 100 m) and the "run time" for which simulated particles are permitted to travel (72 h and 120 h, versus a default of 96 h). These results are presented in Appendix A5.

Altering the altitude at which pollution is emitted (stack height) does not appear to have a notable effect on particle trajectories. This suggests that our results are valid despite assuming equivalent stack heights across all plants in the sample. Shifting stack heights from 100 meters to 10 or 200 meters amounts to a fairly rigorous robustness test, adding to our confidence in our results.

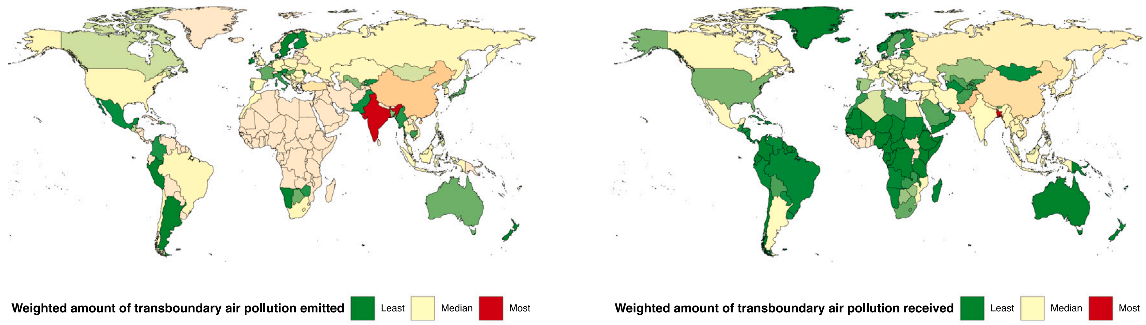

Fig. 1. The amount of transboundary air pollution emitted and received. Estimates of transboundary air pollution loads are weighted by the capacity and SO_2 emissions intensity of the emitting plant and the population of the receiving locality.

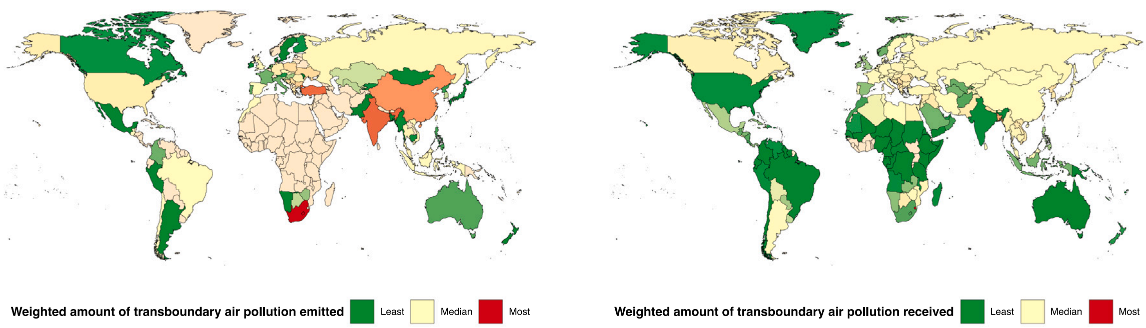

Fig. 2. The amount of transboundary air pollution emitted and received. Estimates of transboundary air pollution loads are weighted by the capacity and SO_2 emissions intensity of the emitting plant and the population of the receiving locality, scaled by the national population of the receiving country.

Table 1
Lists of the largest countries by transboundary pollution emitted and received, the largest countries by the ratio of domestic pollution experienced to foreign pollution experienced and vice versa, and the largest country dyads by the amount of transboundary air pollution emitted and received. Standardized pollution loads are in parentheses. All calculations of transboundary air pollution loads are weighted by the capacity and SO_2 emissions intensity of the emitting plant and linearly scaled according to population of the receiving locality.

Rank	Emitter	Receiver	Domestic:Foreign	Foreign:Domestic	Dyad
1	India (7.584)	Bangladesh (12.963)	Australia (8666)	Bangladesh (701)	India - Bangladesh (45)
2	China (1.919)	Pakistan (3.265)	Chile (7750)	Sweden (649)	India - Pakistan (12)
3	Turkey (0.791)	China (1.986)	India (2575)	Pakistan (510)	China - Vietnam (4)
4	Ukraine (0.136)	Vietnam (1.541)	Colombia (1181)	Argentina (469)	China - South Korea (3)
5	Thailand (0.114)	South Korea (0.75)	United States (276)	Myanmar (82)	India - China (3)
6	Bulgaria (0.061)	Nepal (0.655)	South Africa (272)	Austria (72)	India - Nepal (3)
7	United States (0.027)	Russia (0.574)	Brazil (155)	Cambodia (39)	China - North Korea (2)
8	Vietnam (0.015)	Egypt (0.552)	Guatemala (93)	Croatia (37)	Turkey - Iraq (2)
9	Poland (−0.011)	North Korea (0.537)	Morocco (54)	Canada (29)	China - Japan (2)
10	South Africa (−0.032)	Japan (0.482)	China (49)	Hungary (24)	Turkey - Egypt (2)

Table 2
Lists of the largest countries by transboundary pollution emitted and received and the largest country dyads by the amount of transboundary air pollution emitted and received. Standardized pollution loads are in parentheses. All calculations of transboundary air pollution loads are weighted by the capacity and SO2 emissions intensity of the emitting plant and linearly scaled according to population of the receiving locality. Calculations include adjustments for national populations of receiving countries.

Rank	Emitter	Receiver	Dyad
1	South Africa (4.88)	Swaziland (10.85)	South Africa - Swaziland (39)
2	India (3.58)	Bangladesh (4.78)	India - Bangladesh (18)
3	Turkey (3.5)	Cyprus (1.52)	India - Nepal (6)
4	China (2.51)	Serbia (1.51)	Turkey - Cyprus (6)
5	Bulgaria (0.89)	Macedonia (1.46)	China - North Korea (5)
6	Ukraine (0.59)	Nepal (1.41)	China - Hong Kong (5)
7	Serbia (0.58)	North Korea (1.31)	India - Bhutan (4)
8	Poland (0.55)	Hong Kong (1.27)	India - Pakistan (4)
9	Bosnia and Herzegovina (0.48)	Palestine (1.14)	Turkey - Iraq (4)
10	Greece (0.35)	Moldova (1.03)	China - South Korea (4)

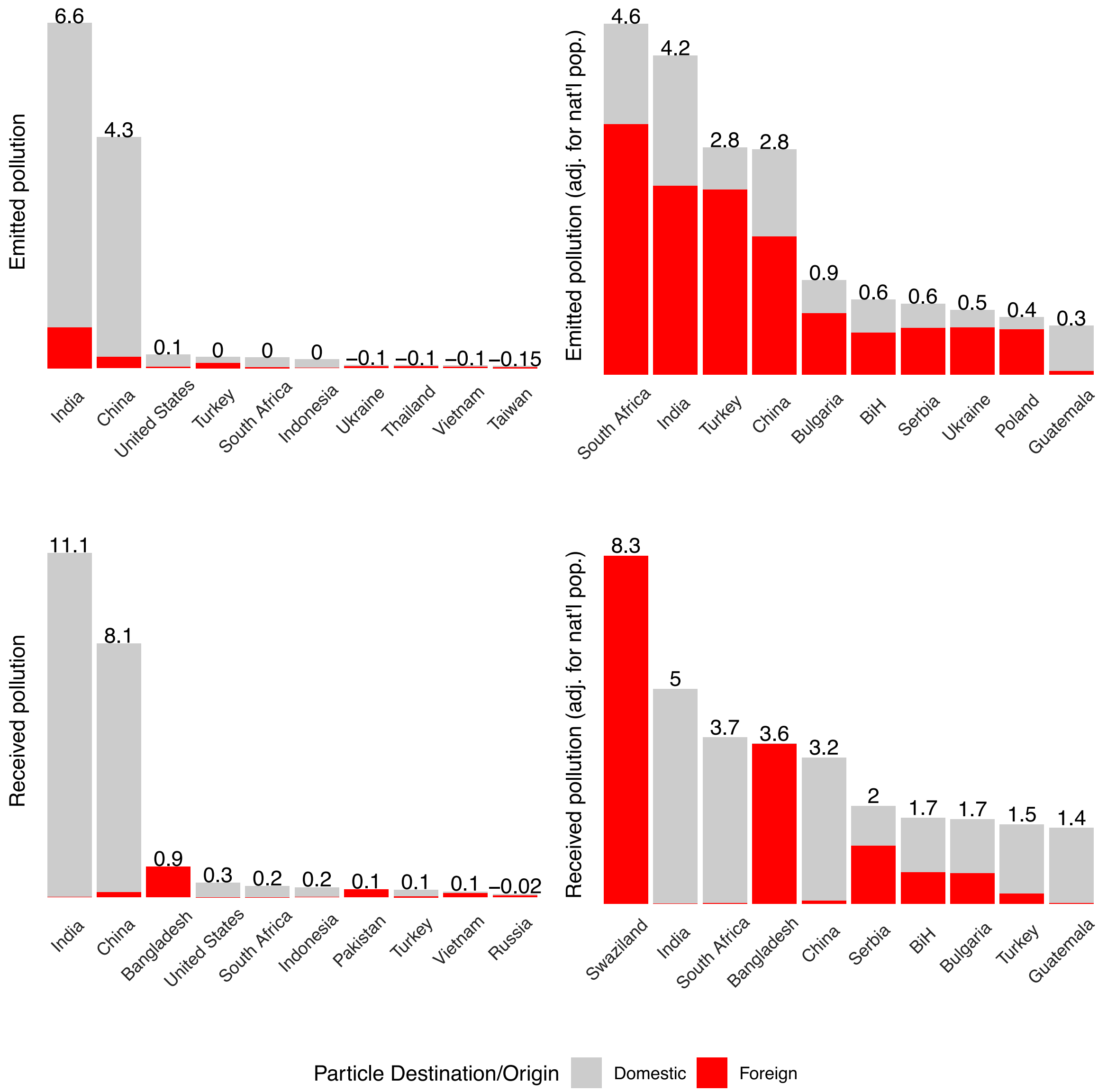

Fig. 3. Pollution emitted (top row) and received (bottom) by country, weighted by plant capacity, SO_2 emissions intensity, and receiving population. Plots on the right adjust for the national populations of receiving countries. Gray bars indicate pollution emitted and experienced domestically. Red bars indicate pollution released overseas. Values atop each bar indicate total pollution loads experienced by each country (standardized). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Changing the run time for emitted particles does have a noticeable effect. As would be expected, a longer run time produces substantially wider particle dispersions, which in turn increase estimated amounts of transboundary air pollution. Nevertheless, the general directions of emitted particles appear largely similar across these alternate tests and the increased dispersion of particles is consistent across plants. This underscores the robustness of our main results.

5.2. Alternative atmospheric models

Though the HYSPLIT model allows us to simulate the trajectories of air pollutants according to meteorological conditions, it does not account for the chemical and physical conversion of pollutants. As we note above, given our focus on the transboundary proportion of pollutant loads at a global scale, it is not feasible to estimate more computationally intensive CTMs for each plant in our dataset. As an alternative, we make use of data generated by the Task Force on Hemispheric Transport of Air Pollution (TF-HTAP), which has conducted multiple simulations to estimate transboundary flows of emissions from industrial activity that take into account these additional complexities of airborne pollutant flows. As a validation check, we compare these HTAP data to the pollutant trajectories estimated through our plant-specific HYSPLIT model; as discussed below, our HYSPLIT results appear similar to the HTAP results.

We obtain HTAP Phase II simulations from the Aerosol Comparisons between Observations and Models Database (AeroCom). Simulations from multiple models are available (Galmarini et al., 2017); we employ data from the GEOS-Chem Adjoint Model given its assessment of changes in pollution levels resulting from particular economic sectors (Henze et al., 2007). With regional "perturbation" simulations for power and industrial sectors, this model enables us to evaluate the role of power plant emissions in determining nearby air quality.

The resolution of GEOS-Chem Adjoint Model is $2° \times 2.5°$. We obtain monthly average fields of near-surface SO_2. Given the importance of Indian and Chinese plants to our main results, we focus on model

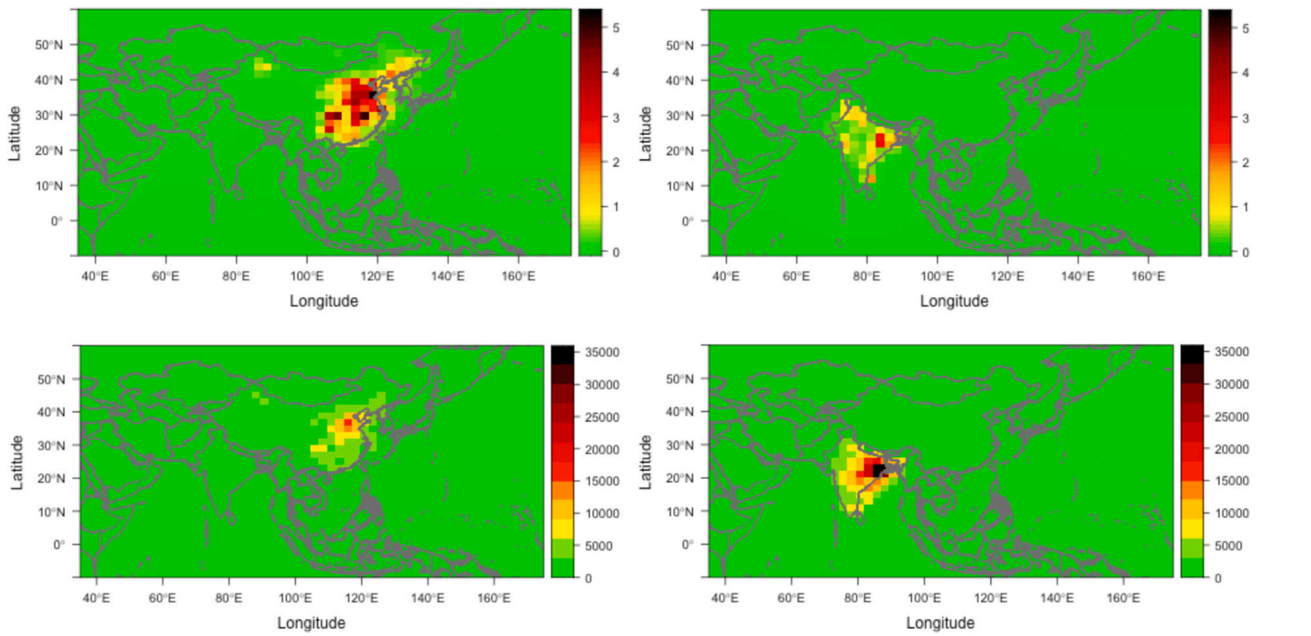

Fig. 4. The top two figures depict the changes in near surface SO_2 (ppbv) concentration resulting from 20% emissions reductions from power plants and industries over East Asia (left) and South Asia (right) estimated from GEOS-Chem adjoint simulations available from the HTAP Phase II. The bottom two figures depict pollution received in given grid cells (SO_2 weighted load) according to our HYSPLIT estimations.

outputs from the global base (BASE) simulation and two counterfactual perturbation simulations that reduce emissions from power plants and industry by 20% in South Asia (SASPIN) and East Asia (EASPIN).

The top two plots in Fig. 4 provide the annual mean SO_2 difference in Asia in the EASPIN and SASPIN models when compared to the BASE scenario; reducing power and industrial sector emissions by 20%, we can see that air quality improves substantially, particularly in eastern areas of China and India. The bottom two plots in Fig. 4 compare these HTAP results to pollution flows estimated through our HYSPLIT model. To make these results comparable, we limit our HYSPLIT data to pollutants released from plants in South and East Asia and estimate pollutant loads received across $2° \times 2.5°$-resolution grid cells.

These lower two plots show that the pollution estimates produced by our HYSPLIT model resemble the trajectories from the HTAP simulations. Comparing estimated pollution loads at the grid cell level, we find a correlation coefficient of 0.854 for cells in East Asia and a correlation coefficient of 0.761 for those in South Asia. The similarity of these results indicate that our HYSPLIT simulation produces an accurate depiction of pollutant flows originating from coal-fired power plants in the region.

As a final test, we average HTAP outputs over grid cells within given countries, allowing us to compare to the country-level figures we find via the HYSPLIT model. In South Asia, the HTAP simulations indicate that grid cells in Bangladesh experience the most industrial pollution on average, which accords with our primary HYSPLIT results. The HTAP results additionally indicate high levels of pollution experienced within India and China, which resembles our results as well. Though the HTAP simulations are not limited to coal-fired power plants, the similarity in results again suggests that the HYSPLIT modeling approach used in this paper is valid. Additional details of these tests are available in Appendix A6.

6. Conclusion

By combining coal-fired power plant data with atmospheric dispersion modeling, our work serves as the first attempt to show the existence, incidence, and consequence of transboundary air pollution from coal-fired power generation at a global scale. Our results demonstrate that contributions and exposure to transboundary pollution are highly uneven across countries and strongly concentrated in South and East Asia. In our primary model, India is found to be the largest emitter of transboundary pollution by a wide margin, while its neighbor Bangladesh is found to receive the most pollution from foreign coal combustion. In a series of sensitivity tests, we find that our results are generally robust to different assumptions being made within the HYSPLIT model. We additionally find that the results from the HYSPLIT model resemble those produced by more complex and computationally intensive models.

Our work speaks to several potential avenues for future research. We rely on *estimates* of potential pollution flows; improvements in satellite imaging technology may eventually allow for researchers to associate "true" or observed pollution flows with specific coal-fired power plants. We additionally detect some evidence of seasonality patterns in transboundary pollutant flows that might be investigated in future work. Furthermore, the capacity weights we use to estimate pollution burdens are based on the nameplate capacities of emitting plants. Not all coal-fired power plants operate at full capacity; future work might probe the effect of accounting for plants' actual operating capacity.

Finally, our results address a potential source of renewed international cooperation on climate change. Political scientists have theorized that countries will be likelier to commit to substantial reductions in greenhouse gas emissions when they generate local, short-term co-benefits like improved air quality (Keohane and Victor, 2016). Problems of severe air pollution in places like China and India, owing to local industrial activity, are well documented (e.g., Roston and Tartar, 2018) and further indicated by our results. The magnitude of *transboundary* air pollution that we document here for China, India, and their neighbors may add to the international pressure placed on major coal-producing countries to adopt stricter pollution measures for coal-fired power plants. There are important caveats to this, however. First, while implementing stricter emissions control technologies may partly relieve the issues of local and regional pollution highlighted here, such "end-of-pipe" control measures have the side effect of increasing electricity usage and intensifying greenhouse gas emissions (Zhao et al., 2017). This suggests that while the transboundary pollution flows we estimate may provide openings for international collaboration, the efforts of pollution-receiving localities may not always be compatible with global climate goals. Second, we find that the vast majority of air pollution from coal combustion in India and China is experienced *domestically*. This suggests that while these countries may be pressured by their neighbors to limit coal use, the strongest impetus for action may emerge from within their own borders.

CRediT authorship contribution statement

Xinming Du: Formal analysis, Investigation, Writing - original draft, Visualization. **Xiaomeng Jin:** Methodology, Software, Formal analysis, Resources. **Noah Zucker:** Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Ryan Kennedy:** Methodology, Software, Formal analysis, Resources. **Johannes Urpelainen:** Conceptualization, Resources, Writing - review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110862.

References

Aguilar, Francisco X., Goerndt, Michael E., Song, Nianfu, Shifley, Stephen, 2012. Internal, external and location factors influencing cofiring of biomass with coal in the U.S. northern region. Energy Econ. 34, 1790–1798.
Alkon, Meir, Wang, Erik, 2018. Pollution lowers support for China's regime: quasi-experimental evidence from Beijing. J. Politics 80 (1), 327–331.
Barrett, Scott, 1990. The problem of global environmental protection. Oxf. Rev. Econ. Policy 6 (1), 68–79.
Barrett, Scott, 2003. Environment and Statecraft: The Strategy of Environmental Policy Making. Oxford University Press, New York.
Benarroch, Michael, Thille, Henry, 2001. Transboundary pollution and the gains from trade. J. Int. Econ. 55, 139–159.
Bernauer, Thomas, Koubi, Vally, 2009. Effects of political institutions on air quality. Ecol. Econom. 68 (5), 1355–1365.
Bernauer, Thomas, Kuhn, Patrick M., 2010. Is there an environmental version of the Kantian peace? insights from water pollution in Europe. Eur. J. Int. Relat. 16 (1), 77–102.
Brulle, Robert J., Pellow, David N., 2006. Environmental justice: Human health and environmental inequalities. Annu. Rev. Public Health 27 (1), 103–124.
Cao, Xun, Prakash, Aseem, 2010. Trade competition and domestic pollution: A panel study, 1980-2003. Int. Organ. 64 (3), 481–503.
Chen, Zhu, Wang, Jin-Nan, Ma, Guo-Xia, Zhang, Yan-Shen, 2013. China tackles the health effects of air pollution. Lancet 382 (9909), 1959–1960.
CIESIN, 2017. Gridded Population of the World, Version 4 (GPWv4): Administrative Unit Center Points with Population Estimates, Revision 10. Center for International Earth Science Information Network, Columbia University, Palisades, NY; NASA Socioeconomic Data and Applications Center (SEDAC).
Coase, Ronald, 1960. Problem of social cost. J. Law Econ. 3, 1–44.
Cole, Matthew A., 2007. Corruption, income and the environment: An empirical analysis. Ecol. Econom. 62 (3), 637–647.
Conconi, Paola, 2003. Green lobbies and transboundary pollution in large open economies. J. Int. Econ. 59 (2), 399–422.
de Leeuw, Frank A.A.M., 2002. A set of emission indicators for long-range transboundary air pollution. Environ. Sci. Policy 5 (2), 135–145.
Dong, Z., Kang, S., Guo, J., Zhang, Q., Wang, X., Qin, D., 2017. Composition and mixing states of brown haze particle over the Himalayas along two transboundary south-north transects. Atmos. Environ. 156, 24–35.
Draxler, Roland R., Hess, G.D., 1998. An overview of the HYSPLIT_4 modelling system for trajectories, dispersion and deposition. Aust. Meteorol. Mag. 47, 295–308.
Duflo, Esther, Greenstone, Michael, Pande, Rohini, Ryan, Nicholas, 2013. Truth-telling by third-party auditors and the response of polluting firms: Experimental evidence from India. Q. J. Econ. 128 (4), 1499–1545.
Ebenstein, Avraham, Fan, Maoyong, He, Guojun, Zhou, Maigeng, 2017. New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. Proc. Natl. Acad. Sci. 114 (39), 10384–10389.
Galmarini, Stefano, Koffi, Brigitte, Solazzo, Efisio, Keating, Terry, Hogrefe, Christian, Schulz, Michael, Benedictow, Anna, Griesfeller, Jan Jurgen, Janssens-Maenhout, Greet, Carmichael, Greg, Fu, Joshua, Dentener, Frank, 2017. Technical note: Coordination and harmonization of the multi-scale, multi-model activities HTAP2, AQMEII3, and MICS-Asia3: Simulations, emission inventories, boundary conditions, and model output formats. Atmos. Chem. Phys. 17, 1543–1555.
Greenstone, Michael, Jack, B. Kelsey, 2015. Envirodevonomics: A research agenda for an emerging field. J. Econ. Lit. 53 (1), 5–42.
Henze, D.K., Hakami, A., Seinfeld, J.H., 2007. Development of the adjoint of GEOS-Chem. Atmos. Chem. Phys. 7, 2413–2433.
Hovi, Jon, Sprinz, Detlef F., Underdal, Arild, 2009. Implementing long-term climate policy: Time inconsistency, domestic politics, international anarchy. Global Environ. Politics 9 (3), 20–39.
Huang, Desheng, Xu, Jianhua, Zhang, Shiqiu, 2012. Valuing the health risks of particular air pollution in the Pearl River Delta, China. Environ. Sci. Policy 15 (1), 38–47.
IEA, 2017. Tracking Clean Energy Progress 2017. International Energy Agency, France.
Jeong, U., Lee, H., Kim, J., Kim, W., Hong, H., Song, C.K., 2013. Determination of the inter-annual and spatial characteristics of the contribution of long-range transport to SO2 levels in Seoul between 2001 and 2010 based on conditional potential source contribution function. Atmos. Environ. 70, 307–317.
Kaldellis, J.K., Chalvatzis, K.J., Spyropoulos, G.C., 2007. Transboundary air pollution balance in the new integrated European environment. Environ. Sci. Policy 10 (7–8), 725–733.
Kasahara, Mikio, Takahashi, Kanji, 1976. Experimental studies on aerosol particle formation by sulfur dioxide. Atmos. Environ. 10 (6), 475–486.
Keating, Terry, Zuber, André, Dentener, Frank, Seddon, Jessica, Travnikov, Oleg, Gusev, Alexy, Carmichael, Greg, Parrish, David, Grano, Doug, 2010. Hemispheric Transport of Air Pollution 2010. Task Force on Hemispheric Transport of Air Pollution, Convention on Long-range Transboundary Air Pollution. Economic Commission for Europe, United Nations, New York and Geneva.
Keohane, Robert O., 1984. After Hegemony: Cooperation and Discord in the World Political Economy. Princeton University Press, Princeton.
Keohane, Robert O., Victor, David G., 2016. Cooperation and discord in global climate policy. Nature Clim. Change 6 (6), 570–575.
Kopas, Jacob, York, Erin, Jin, Xiaomeng, Harish, S.P., Kennedy, Ryan, Shen, Shiran Victoria, Urpelainen, Johannes, 2020. Environmental justice in India: Incidence of air pollution from coal-fired power plants. Ecol. Econom. 176, 106711.
Li, C., Krotkov, N.A., Dickerson, R.R., Li, Z., Yang, K., Chin, M., 2010. Transport and evolution of a pollution plume from northern China: A satellite-based case study. J. Geophys. Res. 115, 1–11.
Mallik, C., Lai, S., Naja, M., Chand, D., Venkataramani, S., Joshi, H., Pant, P., 2013. Enhanced SO2 concentrations observed over northern India. Int. J. Remote Sens. 34 (8), 2749–2762.
Bueno de Mesquita, Bruce, Smith, Alastair, Siverson, Randolph M., Morrow, James D., 2003. The Logic of Political Survival. MIT Press, Cambridge.
Mitchell, Ronald B., 1994. Regime design matters: Intentional oil pollution and treaty compliance. Int. Organ. 48 (3), 425–458.
Moreno, T., Kojima, T., Querol, X., Alastuey, A., Amato, F., Gibbons, W., 2012. Natural versus anthropogenic inhalable aerosol chemistry of transboundary east Asian atmospheric outflows into western Japan. Sci. Total Environ. 424, 182–192.
Myhrvold, N.P., Caldeira, K., 2012. Greenhouse gases, climate change and the transition from coal to low-carbon electricity. Environ. Res. Lett. 7 (1), 014019.
Perrin, Sophie, Bernauer, Thomas, 2010. International regime formation revisited: Explaining ratification behaviour with respect to long-range transboundary air pollution agreements in Europe. Eur. Union Politics 11 (3), 405–426.
Roston, Eric, Tartar, Andrew, 2018. The Dirty Legacy of China's and India's Growth. Bloomberg Businessweek.
Sigman, H., 2002. International spillovers and water quality in rivers: Do countries free ride?. Amer. Econ. Rev. 92 (4), 1152–1159.
Sprinz, Detlef, Vaahtoranta, Tapani, 1994. Interest-based explanation of international environmental policy. Int. Organ. 48 (1), 77–105.
Stangl, Christopher M., Krasnomowitz, Justin M., Apsokardu, Michael J., Tiszenkel, Lee, Ouyang, Qi, Lee, Shanhu, Johnston, Murray V., 2019. Sulfur dioxide modifies aerosol particle formation and growth by ozonolysis of monoterpenes and isoprene. J. Geophys. Res.: Atmos. 124, 4800–4811.
Stern, Nicholas, 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press, New York.

Tong, Dan, Zhang, Qiang, Davis, Steven J., Liu, Fei, Zheng, Bo, Geng, Guannan, Xue, Tao, Li, Meng, Hong, Chaopeng, Lu, Zifeng, Streets, David G., Guan, Dabo, He, Kebin, 2018. Targeted emission reductions from global super-polluting power plant units. Nature Sustain. 1, 59–68.

West, J.J., Naik, V., Horowitz, L.W., Fiore, A.M., 2009. Effect of regional precursor emission controls on long-range ozone transport – part 2: Steady-state changes in ozone air quality and impacts on human mortality. Atmos. Chem. Phys. 9, 6095–6107.

Wolfram, Catherine, Shelef, Orie, Gertler, Paul, 2012. How will energy demand develop in the developing world?. J. Econ. Perspect. 26 (1), 119–138.

Xie, Lunyu, Huang, Ying, Qin, Ping, 2016. Spatial Distribution of Coal-Fired Power Plants in China. In: Resource for Future Discussion Paper Series, pp. 16–25.

Zhao, Haijun, Ma, Weichun, Dong, Hongjia, Jiang, Ping, 2017. Analysis of co-effects on air pollutants and CO2 emissions generated by end-of-pipe measures of pollution control in China's coal-fired power plants. Sustainability 9 (4), 499.