



**HAL**  
open science

# Country-scale trends in air pollution and fossil fuel CO<sub>2</sub> emissions during 2001-2018: confronting the roles of national policies and economic growth

Ruixue Lei, Sha Feng, Thomas Lauvaux

► **To cite this version:**

Ruixue Lei, Sha Feng, Thomas Lauvaux. Country-scale trends in air pollution and fossil fuel CO<sub>2</sub> emissions during 2001-2018: confronting the roles of national policies and economic growth. *Environmental Research Letters*, 2021, 16, 10.1088/1748-9326/abc9e1 . insu-03660178

**HAL Id: insu-03660178**

**<https://insu.hal.science/insu-03660178>**

Submitted on 5 May 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

LETTER • OPEN ACCESS

## Country-scale trends in air pollution and fossil fuel CO<sub>2</sub> emissions during 2001–2018: confronting the roles of national policies and economic growth

To cite this article: Ruixue Lei *et al* 2021 *Environ. Res. Lett.* **16** 014006

View the [article online](#) for updates and enhancements.

You may also like

- [Vegetation fires, absorbing aerosols and smoke plume characteristics in diverse biomass burning regions of Asia](#)  
Krishna Prasad Vadrevu, Kristofer Lasko, Louis Giglio *et al.*
- [Aerosol interactions with African/Atlantic climate dynamics](#)  
F Hosseinpour and E M Wilcox
- [Variability and trends of aerosol properties over Kanpur, northern India using AERONET data \(2001–10\)](#)  
Dimitris G Kaskaoutis, Ramesh P Singh, Ritesh Gautam *et al.*

ENVIRONMENTAL RESEARCH  
LETTERS

## LETTER

## OPEN ACCESS

RECEIVED  
22 July 2020REVISED  
21 September 2020ACCEPTED FOR PUBLICATION  
12 November 2020PUBLISHED  
18 December 2020

Original content from  
this work may be used  
under the terms of the  
[Creative Commons  
Attribution 4.0 licence](#).

Any further distribution  
of this work must  
maintain attribution to  
the author(s) and the title  
of the work, journal  
citation and DOI.

Country-scale trends in air pollution and fossil fuel CO<sub>2</sub> emissions during 2001–2018: confronting the roles of national policies and economic growthRuixue Lei<sup>1</sup> , Sha Feng<sup>1</sup> and Thomas Lauvaux<sup>1,2</sup> <sup>1</sup> Department of Meteorology and Atmospheric Science, The Pennsylvania State University, University Park, PA 16802, United States of America<sup>2</sup> Laboratoire des Sciences du Climat et de l'Environnement, CEA, CNRS, UVSQ/IPSL, Université Paris-Saclay, Orme des Merisiers, Gif sur Yvette 91191, FranceE-mail: [rlei@psu.edu](mailto:rlei@psu.edu)**Keywords:** fossil fuel CO<sub>2</sub>, ODIAC, AOD, MODIS, GDP, climate policy, environmental Kuznets curveSupplementary material for this article is available [online](#)**Abstract**

Fossil fuel (FF) burning, the main energy source of the modern world's economy, remains the major source of anthropogenic carbon dioxide (CO<sub>2</sub>) and pollutants in the atmosphere. Based on 18 years (2001–2018) of aerosol optical depth (AOD) data from Moderate Resolution Imaging Spectroradiometer satellite, FFCO<sub>2</sub> emissions from the Open-Data Inventory for Anthropogenic Carbon dioxide, and gross domestic product (GDP) data from the World Bank, we found that air quality, FF consumption, and economy are strongly bonded at the continental scale but decoupled at the national level under favorable policies. The comparison of AOD vs PM<sub>2.5</sub> and NO<sub>2</sub> over urbanized areas shows that the pollutants leading to the AOD load can vary significantly by country. A strong connection between GDP and FFCO<sub>2</sub> emissions indicates that economic growth deeply relies on FF consumption in most countries. Meanwhile, air pollution is more associated with the growing trend than the level of development of a country. With more mature technologies and renewable energy, economies can keep growing without compromising their environment and population health.

**1. Introduction**

Fossil fuel (FF) combustion represents the main source of anthropogenic carbon dioxide (CO<sub>2</sub>) released into the atmosphere, primarily driven by the world's economy and its long-lasting emission–energy–economy relationship (Raupach *et al* 2007). The National Oceanic and Atmospheric Administration (NOAA) Annual Greenhouse Gas Index (AGGI), representing the direct radiative forcing due to the accumulation of greenhouse gases in the atmosphere, has increased by 41% since the onset of the industrial revolution (NOAA 2018). Among these gases, fossil fuel carbon dioxide (FFCO<sub>2</sub>) remains by far the largest contributor to AGGI. In response to the rapid increase in atmospheric CO<sub>2</sub> abundance directly contributing to climate changes, vigorous FF emission mitigation policies and regulations have

been drafted to achieve carbon neutrality in the coming decades (UNFCCC 2015). Combustion processes also emit a large number of pollutants (Lu *et al* 2013, Lin *et al* 2018, 2019b) responsible for various harmful effects on human health (Pope *et al* 1995, Grigg 2002, Balakrishnan *et al* 2019, Soriano *et al* 2020, Thakrar *et al* 2020, Yin *et al* 2020). At the sectoral level, limiting FF consumption was considered having significant co-benefits in the cement industry (Tan *et al* 2016), coal-fired power industry (Mao *et al* 2014), and transportation (Creutzig and He 2009, Giles-Corti *et al* 2010). The relevant technical paths (Mao *et al* 2014, Tan *et al* 2016), climate and energy policies (He *et al* 2010, Mayrhofer and Gupta 2016), and health benefits (Giles-Corti *et al* 2010, West *et al* 2013) have been documented. Despite the potential co-benefits of joint mitigation policies (Maione *et al* 2016) and their resulting cost benefits (Markandya

et al 2018), national air quality and CO<sub>2</sub> mitigation policies remain widely disconnected, highly region-specific, and dependent on the growth of national income (West et al 2013, Workman et al 2018).

Due to the reactivity of atmospheric trace gases and uncertainties in emissions, the relationships between CO<sub>2</sub> concentrations and the co-emitted pollutants are complex (Lu et al 2013, Zhao et al 2013). Emissions products like EDGAR-HTAP (Janssens-Maenhout et al 2015), PKU-Fuel (Meng et al 2017), Hestia (Gurney et al 2012), MIX (Li et al 2017), or CDIAC (Andres et al 2011) are critical to examine these relationships, but the uncertainties in FFCO<sub>2</sub> emission inventories remain large due to highly uncertain energy use data and emission factors. Another limitation to defining the relationships among gases and tracking jointly air quality and FFCO<sub>2</sub> emissions at the country scale comes from the absence of a sufficiently dense global long-term monitoring network. Despite the recent increase in satellite observations of atmospheric CO<sub>2</sub> (e.g. OCO-2/3, GOSAT-2), FFCO<sub>2</sub> remains difficult to determine accurately from space due to cloud coverage, aerosol contamination, biogenic contributions, and a limited density of soundings near urban centers (Ye et al 2020). Relationships among trace gases have already been used to determine the combustion factors over different regions of the world (Silva and Arellano 2017). But the current relationships between air quality and FFCO<sub>2</sub> emissions over various countries have been based primarily on inventory estimates rather than direct measurements (e.g. NO<sub>2</sub> over the US (Jiang et al 2018)).

The correlation and causality between CO<sub>2</sub> emissions and gross domestic product (GDP) have been established for many countries (Li et al 2008, Lotfalipour et al 2010, Hatzigeorgiou et al 2011, Pao and Tsai 2011, Ishida 2013, Lu et al 2013). The environmental Kuznets curve (EKC) hypothesis (Kuznets 1955) has been used to describe the change of the relationship between CO<sub>2</sub> emissions and economic indicators like GDP per capita (Jalil and Mahmud 2009, Bilgili et al 2016), financial inclusion (Renzhi and Baek 2020), and economic complexity (Pata 2020), i.e. environmental pressure increases with income up to a certain level until it decreases. But EKC is not always valid. For example, foreign trade leads to increases in per capita CO<sub>2</sub> emissions in the long run as per capita GDP increases, e.g. Indonesia (Saboori et al 2012). While EKC describes the changes in a country over time, the 'flying-geese' model (Bernard and Ravenhill 1994) describes the links between countries which explain the 'catching-up' process of industrialization in late-comer economies. The 'flying S' model extended the 'flying-geese' model (Lin et al 2019a) by validating that the per capita CO<sub>2</sub> emission curve in some countries will mirror that of 'leading geese' countries in the same 'flying-geese' group. Besides,

the strength of the relationship between CO<sub>2</sub> emissions and GDP may vary by regions (Li et al 2008), by periods (Tucker 1995, Hannesson 2009), and by fuel types (Lotfalipour et al 2010). Although climate policies (Payne 2011), energy research and development sources (Wong et al 2013), nuclear energy (Al-mulali 2014), and renewable energy (Tiwari 2011, Amin et al 2020, Pata 2020, Usama et al 2020, Vural 2020) are found having the potential to drive economic growth and decrease CO<sub>2</sub> emissions at the same time, decoupling CO<sub>2</sub> emissions from economic growth has not been successfully demonstrated yet (Hatzigeorgiou et al 2011, Newman 2017). Thus, the compacity between reasonable GDP growth rates and reductions in CO<sub>2</sub> emission levels is a critical issue when considering increasing energy efficiency (Lozano and Gutierrez 2008).

While tracking air quality at the local scale has been primarily based on *in situ* local air monitoring networks (e.g. United States Environmental Protection Agency (EPA) outdoor monitors, <http://aqicn.org>), global country-scale indicators rely primarily on satellite measurements, e.g. Moderate Resolution Imaging Spectroradiometer (MODIS) and ozone monitoring instrument (OMI). Among others, aerosol optical depth (AOD) (Hu and Rao 2009, Xiao et al 2015, Li and He 2018, Zhao et al 2018), particulate matters (PM) (Dinda et al 2000, Lu et al 2013), SO<sub>2</sub> (Kaufmann et al 1998, Cole 2000, Dinda et al 2000, Buehn and Farzanegan 2013, Lu et al 2013, Guo et al 2017) and NO<sub>x</sub> (Cole 2000, Buehn and Farzanegan 2013, Lu et al 2013) have often been used as proxies of air pollution when examining the relationship between air quality and the economy at large scales. The relationships between them range from strong (Lu et al 2013, Zhao et al 2018), weak (Guo et al 2017), EKC (Cole 2000, Buehn and Farzanegan 2013, Amirnejad and Kordi 2014), inverse EKC (Kaufmann et al 1998, Dinda et al 2000), decreasing in the ratio of pollution/GDP (Muller 2014, Zhao et al 2018) or spatially correlated (Li and He 2018), varying by countries, time lengths, and gas species.

Although the above-mentioned studies have focused on the relationships by the pairs between air pollution, FFCO<sub>2</sub> emissions, and economic growth, no study has examined jointly these three matrices to determine their relationships over the long-term or across the globe. We filled this gap by using 18 years (2001–2018) of AOD data from MODIS satellite, FFCO<sub>2</sub> emissions from the Open-Data Inventory for Anthropogenic Carbon dioxide (ODIAC), and GDP data from the World Bank. We aimed at answering the following questions: What are the relationships between air quality, FFCO<sub>2</sub> emissions, and the economy at national levels? Moreover, is air pollution more associated with the economic growth rate or the actual level of development? Are the relationships inherently bonded or can they be decoupled under favorable policies?

## 2. Data and methods

To investigate the relationship between air pollution, FF consumption, and economic growth at the country level, we used AOD, FFCO<sub>2</sub> emission, and GDP as their proxies, respectively. AOD was used as a proxy of air pollution in multiple studies (Hu and Rao 2009, Xiao *et al* 2015, Li and He 2018, Zhao *et al* 2018). Due to the lack of a dense dataset of satellite XCO<sub>2</sub> measurements, we used the global monthly FFCO<sub>2</sub> emissions at a 1° × 1° resolution from ODIAC version 2019 (Oda *et al* 2018). ODIAC combined satellite nightlight data, national energy consumption statistics, and power plant emission/location profiles to estimate the global spatial extent of FFCO<sub>2</sub> emission. ODIAC has been applied by the international research communities for a wide range of research, like CO<sub>2</sub> flux inversions (Maksyutov *et al* 2013), urban emission estimation (Lauvaux *et al* 2016), and observing system design experiments (Ye *et al* 2020). We calculated the annual country-level FFCO<sub>2</sub> emissions by summing up grid points in the country masks which is generated by rasterizing an ArcGIS counties data package. Since we focus on FF emission in this study, we applied a 0.1 g C m<sup>-2</sup> d<sup>-1</sup> (C = Carbon) FF emission mask to select urbanized areas of a given country where anthropogenic sources dominate the observed enhancements and exclude the other CO<sub>2</sub> sources like biomass burning. The determination of the mask threshold and its impact are shown in figures S1 and S2, which are available online at <https://stacks.iop.org/ERL/16/014006/mmedia>. All country-level variables (GDP, AOD, FFCO<sub>2</sub> emission, PM<sub>2.5</sub> and NO<sub>2</sub>) in the following analysis are filtered by 0.1 g C m<sup>-2</sup> d<sup>-1</sup> emission mask. We used emission masks instead of a land-use cover map because land-use cover only provides a description of the urban area, which often excludes point source emissions such as power plants. Hence, we use emission masks to include all possible areas that contribute significantly to FF emissions. The country-level GDP and GDP per capita (constant 2010 US\$) were obtained from World Development Indicators (WDI) published by the World Bank. Since current world economy is still heavily dependent on high carbon energy sources (Jean-Baptiste and Ducroux 2003), FFCO<sub>2</sub> emissions remain a robust indicator of economic development.

For AOD, we chose the AOD data from MODIS due to high spatial resolution and the longest temporal range compared to other satellites. The MODIS Aerosol Product, 'MOD04\_L2—MODIS/Terra Aerosol 5-Min L2 Swath 10 km' (Levy and Hsu 2015), starting available from 24 February 2000, was used for the analyses. To ensure data quality, only data points with AOD\_550\_Dark\_Target\_Deep\_Blue\_Combined\_QA\_Flag 2 and 3 (good and very good) are kept. We re-gridded AOD at native grids to 1° × 1° each month

to avoid uneven sampling issues. Then the annual mean of the AOD data at 1° × 1° was calculated for further analysis.

Although AOD is commonly used as a proxy for surface PM<sub>2.5</sub> (particles smaller than 2.5 μm median diameter), the other sources such as dust, wildfire, and biomass burning can also lead to high AOD. We excluded these components from this study as both natural and human drivers can impact them. Hence, we limited the analysis to the area where FFCO<sub>2</sub> emissions are greater than 0.1 g C m<sup>-2</sup> d<sup>-1</sup>. Both the annual mean and trend of AOD may vary with the different emission masks. We examined in detail the effect of our high-FFCO<sub>2</sub> emission mask threshold in figure S2 for large countries like China, the USA, and India.

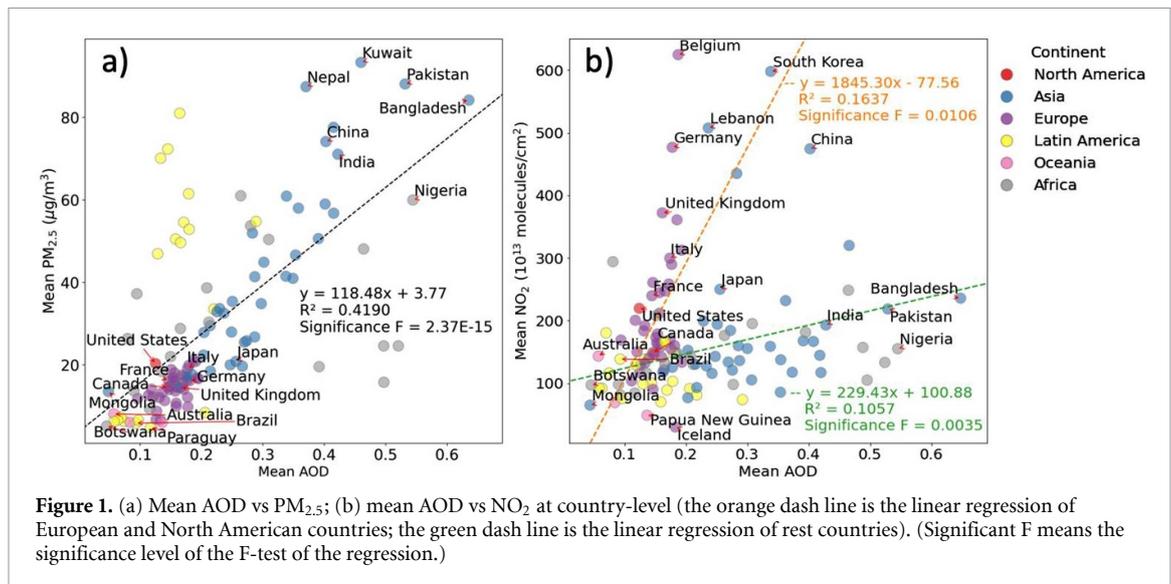
Note that the drivers of air pollution vary across countries. A signal proxy may not represent the entire array of air pollutants. Thus, we compared AOD with PM<sub>2.5</sub> and NO<sub>2</sub>, two major pollutants from various anthropogenic sources, to examine the primary drivers of AOD across countries. The major anthropogenic sources of PM<sub>2.5</sub> originate from the industrial and commercial, transportation, food and agriculture, and the residential sectors, while anthropogenic NO<sub>2</sub> emissions are mainly from industrial and commercial, and transportation sectors (Thakrar *et al* 2020). The monthly 0.25° × 0.25° global PM<sub>2.5</sub> was obtained from CAMS global reanalysis (Inness *et al* 2019). Monthly 0.125° × 0.125° global tropospheric NO<sub>2</sub> was from the OMI (Boersma *et al* 2011). Note that PM<sub>2.5</sub> started available from 2003 and NO<sub>2</sub> started available from 2005, we therefore selected AOD vs PM<sub>2.5</sub> in 2003–2018 and AOD vs NO<sub>2</sub> in 2005–2018 for comparison. Similar to AOD, the original monthly PM<sub>2.5</sub> and NO<sub>2</sub> are re-gridded to 1° × 1° before calculation of annual means, then the same 0.1 g C m<sup>-2</sup> d<sup>-1</sup> FFCO<sub>2</sub> emission mask was applied to the country-level annual means for the comparison.

We studied the relationship between AOD, FFCO<sub>2</sub> emissions, and GDP in terms of annual mean and trend. The trend was denoted by the slope of the linear regression. Here, in order to normalize GDP and FFCO<sub>2</sub> emissions across countries of various sizes and carbon intensities, we used GDP per capita and FFCO<sub>2</sub> emission per area in the linear regression. Note that AOD itself is a normalized parameter. All variables in the country-level in this study are shown in figure S3.

## 3. Results

### 3.1. The causes of air pollution

AOD measures the total abundance of aerosols in the atmosphere. The main anthropogenic activities resulting in high AOD emissions are industries and traffic (Kumar 2010). Due to the variability in human

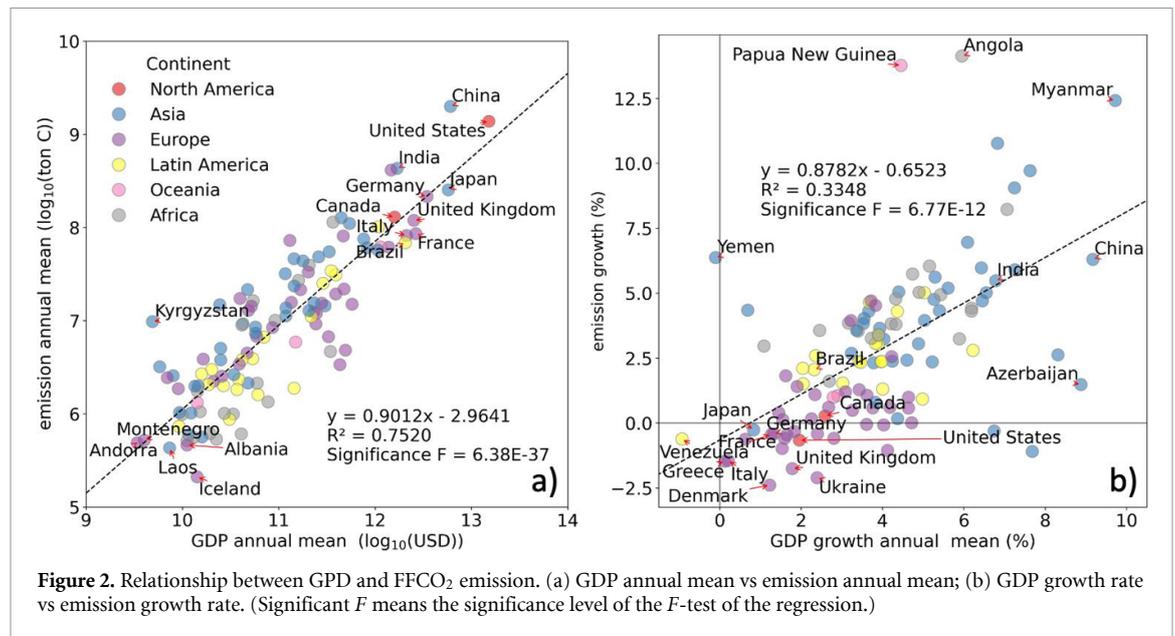


activities across the world, we expect to use the relationship of AOD with  $PM_{2.5}$  and  $NO_2$  alternatively to find out the causes of air pollution for a given country (figure 1). A fairly robust linear relationship between AOD and  $PM_{2.5}$  at the country-level can be found ( $R^2 = 0.42$ ) in figure 1(a), which is consistent with previous studies (Green *et al* 2009, Xie *et al* 2015, You *et al* 2016). Some countries in Latin America, one of the most urbanized areas of the world with nearly 80% of the population living in cities, have higher ratios of  $PM_{2.5}$  to AOD, as documented in previous studies (e.g. Gouveia *et al* 2019). Asian and African (especially the Middle East) countries tend to hold much higher AOD and  $PM_{2.5}$  than countries in other continents, implying different industries, energy source mixes, and/or emission regulations. According to WDI, industry (including construction) as a percentage of GDP in East Asia and Pacific, Latin America and Caribbean, European area, and North America are 35.48%, 27.89%, 22.47%, and 20.42% in 2003–2018 on average, respectively, while the manufacturing as percentage of GDP are 24.20%, 14.29%, 14.91%, and 12.10% in 2003–2018 on average, respectively. In other words, Asia has a higher percentage of industry in GDP and its manufacturing also accounts for a higher proportion of industry than other regions. Note that since a small number of grid points are kept after applying our  $0.1 \text{ g C m}^{-2} \text{ d}^{-1}$  mask over Africa, Latin America, and Oceania, the selected area of a given country may not match its economic structure of the whole country. Hence, we focus on sufficiently large countries for which significant fractions of their urbanized surfaces have been preserved. This sector-driven difference can also be seen in the relationship between AOD and  $NO_2$  (figure 1(b)). Most Asian and African countries have smaller slopes, while European countries show a steep slope. Note that China and South Korea have a larger slope than other Asian countries.

Although they have legislation on  $PM_{2.5}$  and  $NO_x$  ( $NO + NO_2$ ) controlling (Mosteller 2016, Transportpolicy n.d.), controlling  $NO_x$  is more difficult than  $PM_{2.5}$ . Control efficiency of  $PM_{2.5}$  can reach 85%–99% by using simple physical measures like Baghouse and Wet Scrubbing while the similar control efficiency of  $NO_x$  usually requires ‘selective catalytic reduction’ (EPA 2007). These countries have relatively lower AOD but still higher  $NO_2$  compared to other Asian countries.

### 3.2. Relationship between fossil fuel consumption and economy

Figure 2 shows the relationship between FFCO<sub>2</sub> emissions and GDP at the country-level, in terms of annual mean and growth rate. The linear regression between the mean GDP and FFCO<sub>2</sub> emissions (figure 2(a)) shows a strong correlation ( $R^2 = 0.75$ ) in the logarithmic scale, while their growth rates are overall linearly correlated but to a lesser extent ( $R^2 = 0.33$ ) (figure 2(b)). The linear relationship between GDP and FFCO<sub>2</sub> emissions indicates that the world economy is still heavily dependent on high carbon energy sources, which is also documented by (Jean-Baptiste and Ducroux 2003). However, in detail, the world’s largest economies have slightly different relationships between the GDP and FF emission growth rates. While Asian, Latin American, and African countries show increasing FFCO<sub>2</sub> growth rates corresponding to fast-growing economies, the major European countries and the United States fall in the increasing-GDP-and-decreasing-FFCO<sub>2</sub>-emission quadrant, implying that these developed countries have been able to slow down their carbon intensity while growing their economies. We also notice that some developing countries like Tajikistan or Uzbekistan have over 6% GDP growth but negative FFCO<sub>2</sub> emission growth, as the result of their major industries being tourism and agriculture



**Figure 2.** Relationship between GDP and FFCO<sub>2</sub> emission. (a) GDP annual mean vs emission annual mean; (b) GDP growth rate vs emission growth rate. (Significant *F* means the significance level of the *F*-test of the regression.)

instead of heavily relying on carbon energy sources.

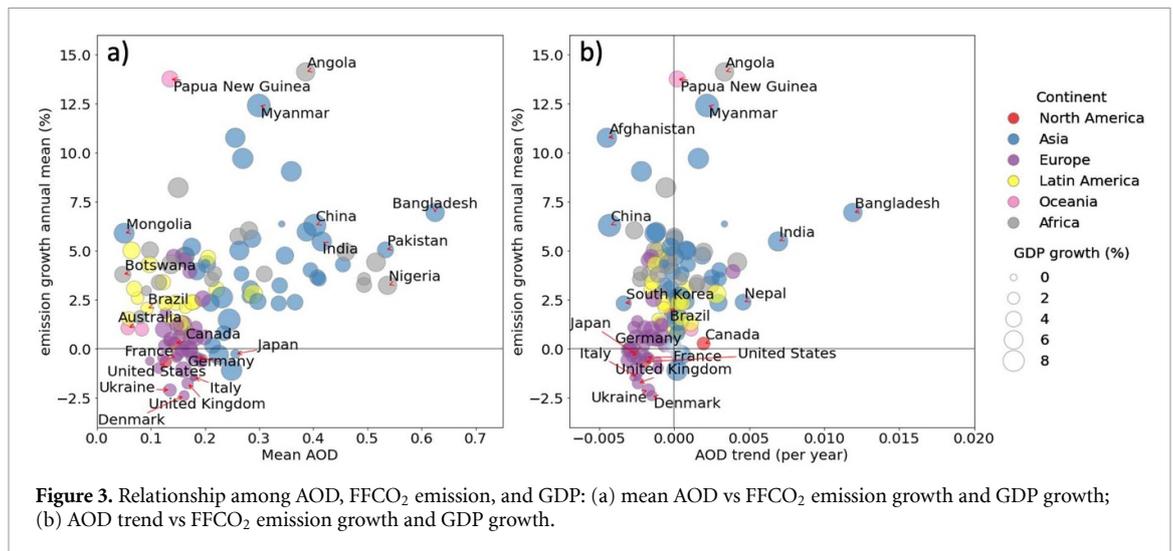
### 3.3. Relationship of air pollution vs fossil fuel consumption and economy

Asian and African countries are in general more polluted than European and American countries (figures 3(a) and S4(a), (b)). Although the AOD does not show a clear linear correlation with the FFCO<sub>2</sub> emission growth, the world economies are clustered into different groups (figure 3(a)). Most Asian and African countries have a common feature of high mean AOD along with high FFCO<sub>2</sub> emission growth, while the European and American countries are clustered showing low mean AOD and low FFCO<sub>2</sub> emission growth. Similar features can be found in the relationship between mean AOD and GDP growth (figure S4(b)). On the one hand, under-developed Latin American countries do not rely on heavily polluting industries and developed European countries enforce effective regulations and policies to control air pollution. They both show low AOD and low FFCO<sub>2</sub> emission growth rates. On the other hand, fast-growing-developing countries, such as China, Indian, and Bangladesh, show high AOD and high FFCO<sub>2</sub> emission growth rates. The control policies for both FF burning and air pollution still face challenges. The air pollution becomes a by-product of the fast-growing economy, which is not necessarily linked to the average consumption of the energy (mean emission per area in figure S5(a)) and the wealth level (mean GDP per capita in figure S5(b)) of the countries.

The relationships between the economy, FF energy consumption, and air pollution trend at the country-level resemble the regional separation described above. Most Asian and African countries show increasing AOD trends during 2001–2018, while

most European countries and the United States show decreasing AOD trends (figures 3(b) and S4(c), (d)). The AOD trend also is linked to FFCO<sub>2</sub> (figures 3(b) and S4(c)) and GDP (figure S4(d)) growth rate rather than their means (figure 5(c), (d)). Most Asian and African countries are in the increasing-AOD-trend-and-increasing-fossil-fuel-emission-growth-rate quadrant and the increasing-AOD-trend-and-increasing-GDP-growth-rate quadrant, while most European countries and the United States fall in the decreasing-AOD-trend-and-decreasing-fossil-fuel-emission-growth-rate quadrant or the decreasing-AOD-trend-and-low-fossil-fuel-emission-growth-rate quadrant. For most economies, the AOD trend still appears correlated with the growing trend of development. Interestingly, the air quality in the Latin American countries remains almost the same, while both of their FF emissions and GDP growth rates increase. Consistent with the AOD annual mean analysis, effective regulation and policies can decrease air pollutions and FF emission burning as the economy grows.

Few countries do not fall into the general quadrants described above. Both Afghanistan and China have fast GDP and FFCO<sub>2</sub> emission increase rates with a decreasing AOD trend. While Afghanistan may have too few data points after applying the 0.1 g C m<sup>-2</sup> d<sup>-1</sup> FFCO<sub>2</sub> emission mask, China is large enough to have a statistically significant sample size. With recent national policies tightening its air quality standards since 2014 (Transportpolicy 2012), the decrease in AOD is mostly explained by regulations on emissions. Canada, as a developed country, also appears as an outlier. Its FFCO<sub>2</sub> emissions remain constant in the period of interest but with a positive AOD trend. The high AOD values being mostly visible in the western part of Central Canada and downwind, this increase seems related to the increase in oil



**Figure 3.** Relationship among AOD, FFCO<sub>2</sub> emission, and GDP: (a) mean AOD vs FFCO<sub>2</sub> emission growth and GDP growth; (b) AOD trend vs FFCO<sub>2</sub> emission growth and GDP growth.

and gas production from oil sands in the past decade, mostly located in the province of Alberta (Natural Resources Canada 2020). These examples highlight the impact of national policies and energy extraction on air quality. Overall, we conclude that the relationship between FFCO<sub>2</sub> emissions and AOD remains difficult to establish, but the overall national-scale trends are clearly visible, showing that air quality and climate policies are mostly disconnected and highly dependent on policies.

#### 4. Discussion

In this study, we chose AOD, FFCO<sub>2</sub> emission, and GDP as the proxies of air quality, FF consumption, and economy, respectively. We demonstrated that at the national scale, these proxies are valid, but their interpretation varies slightly. AOD shows a positive relationship with PM<sub>2.5</sub> that directly affects human health. PM<sub>2.5</sub> is a better indicator of air pollution, but the country-level estimates of PM<sub>2.5</sub> for the period of interest are not readily available. NO<sub>2</sub> is another indicator of air pollution, but the temporal coverage of OMI data is too short to examine long-term trends. Another high-resolution NO<sub>2</sub> satellite TROPospheric Monitoring Instrument (TROPOMI) was launched on 13 October 2017 (Veefkind *et al* 2012), significantly increasing the sampling size and resolution in the future studies.

The satellite-measured XCO<sub>2</sub> from GOSAT and OCO-2/3 could be a proxy of the climate response to the FF burning, but extracting the FF contribution from XCO<sub>2</sub> retrievals remain laborious, in addition to the limitations due to the small sampling size and coverage near urban centers (Ye *et al* 2020, Zheng *et al* 2020). We also tried to isolate anthropogenic CO<sub>2</sub> by using spatial XCO<sub>2</sub> anomaly along with the latitude band (Hakkarainen *et al* 2018), but the anomaly failed to reflect the local changes in FFCO<sub>2</sub> emission. In future studies, the combination of NO<sub>2</sub> retrievals

from TROPOMI and XCO<sub>2</sub> retrievals from OCO-3 will provide more detailed information on the relationships between trace gases.

GDP is a commonly used proxy of economic status, but it contains large variability of economic activities albeit many of them are not directly linked to air pollution and FF. Non-Green GDP may be a better metric to reflect the effects of anthropogenic activities on air quality. However, the global country-level non-green GDP database is not robust enough due to the complexity of measuring and tracking the fraction of the GDP from greener energies.

We focused our analysis on the anthropogenic drivers when discussing the relationship between AOD, FFCO<sub>2</sub> emission, and GDP. Although we applied 0.1 g C m<sup>-2</sup> d<sup>-1</sup> FFCO<sub>2</sub> emission mask to screen out AOD and CO<sub>2</sub> natural sources, some caveats need to be pointed out. Firstly, this method cannot perfectly separate areas affected by natural and anthropogenic sources. Secondly, the results for small-sized countries may not be significant due to the limited number of data points in the analyses after applying our emission masks. Overall, our approach was successful for large countries where biomass burning remains limited. The natural variability remains smaller than anthropogenic variations at the decadal timescale, but the impact of regional climate changes on AOD might become increasingly important in the coming decades.

The relationships of AOD with PM<sub>2.5</sub> and NO<sub>2</sub> suggest that the sources of air pollution vary widely across countries. Thus, the relationship between air pollution and the economy may vary when different proxies were chosen. In other words, economic systems may be more associated with some pollutants than others. Note that European countries have a higher NO<sub>2</sub>/AOD ratio than Asian and African countries. But nowadays some Asian countries, e.g. China, Japan, and South Korean, tend to resemble European countries. It implies that the main drivers of air

pollution will change over time as countries transition from manufacturing economies to service economies. The transition may be also accompanied by changes in the type of energy sources which may also affect the FFCO<sub>2</sub>. For example, using more renewable energy may slow down the growth rate of, or even decrease, CO<sub>2</sub> emissions (Amin *et al* 2020, Pata 2020, Usama *et al* 2020, Vural 2020). Therefore, policies to optimize the energy structure may benefit in multiple ways.

We use AOD from the MODIS satellite as a proxy of air pollution in this study for the country-level comparisons. This study has demonstrated the capacity of the long-term monitoring of satellite missions. With additional gases become available from satellite missions (e.g. CO and NO<sub>2</sub> from TROPOMI), more detailed investigation becomes feasible in the future.

We only studied the relationships among AOD, FFCO<sub>2</sub> emission, and GDP based on scope 1 emissions (direct emissions from owned or controlled sources). In future work, scope 2 (indirect emissions from purchased energy) and scope 3 emissions (indirect emissions from imported goods) could be also taken into consideration. The current strong bonds between energy consumption and economy are temporary as emerging economies are experiencing the top of the EKC (Zhao *et al* 2018, Dong *et al* 2019). Hence, we expect these relationships to evolve rapidly in the coming decade especially in Asia where GDP growth rates have slowed down, while African nations tend to develop faster and hence are likely to experience rapid growth in air pollution and CO<sub>2</sub> emissions (Lioussé *et al* 2014). Considering the limits mentioned above, combining econometric analysis and more data representing specific sectors or aspects of the national economies in future work could fundament our findings in a wider scope.

## 5. Conclusions

By investigating the relationships among AOD, FFCO<sub>2</sub> emission, and GDP at country-levels in 2001–2018, we found that air quality, FF consumption, and economy are strongly bonded at the continental scale but decoupled at the national scale under favorable policies.

The comparison of AOD vs PM<sub>2.5</sub> and NO<sub>2</sub> over urbanized areas shows that the pollutants leading to the AOD load can vary significantly by country. Although AOD is correlated with PM<sub>2.5</sub> for almost all countries, its linkage to NO<sub>2</sub> can only be seen in some Asian and African countries. It suggests that the main sectors and energy types causing air pollution differing across countries, which requires more targeted environmental control procedures to address air pollution issues.

A strong connection between GDP and FFCO<sub>2</sub> emission indicates that economic growth deeply

replies on FF consumption in most countries. Meanwhile, air pollution is more associated with the growing trend instead of the level of development of a country. Note that the connections between the three indicators are stronger in developing countries than in developed countries. On the contrary, some developed countries in Europe maintained positive GDP growth with decreasing FFCO<sub>2</sub> emission and negative AOD trends in recent two decades. Some developing countries, i.e. China, even maintained fast GDP and FFCO<sub>2</sub> emission growth while their AOD decreased rapidly in the same period thanks to national emission mitigation policies.

This study, relying on long-term satellite data, demonstrates that economic development and air pollution are not inherently bonded and can be decoupled under favorable policies. With more mature technologies and renewable energy, economies can keep growing without compromising the environment and public health.

## Data Availability

Any data that support the findings of this study are included within the article (and any supplementary information files).

ArcGIS countries data package: <https://www.arcgis.com/home/item.html?id=f9a37f7add4e402a9df16230b26272ed>

AOD from MODIS: [https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD04\\_L2/](https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD04_L2/)

NO<sub>2</sub> from OMI: [https://www.temis.nl/airpollution/no2col/no2regioomimonth\\_qa.php](https://www.temis.nl/airpollution/no2col/no2regioomimonth_qa.php)

PM<sub>2.5</sub> from CAMS: <https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-reanalysis-eac4-monthly?tab=form>

FFCO<sub>2</sub> emission from ODIAC: [http://db.cger.nies.go.jp/dataset/ODIAC/DL\\_odiad2019.html](http://db.cger.nies.go.jp/dataset/ODIAC/DL_odiad2019.html)

WDI from World Bank: <http://datatopics.worldbank.org/world-development-indicators/>

## Acknowledgments

This work has been funded by the National Aeronautics and Space Administration (NASA) Grant No. #80NSSC19k0093. This work was also supported by the French research program Make Our Planet Great Again (Project CIUDAD).

## ORCID iDs

Ruixue Lei  <https://orcid.org/0000-0001-6226-7075>

Sha Feng  <https://orcid.org/0000-0002-2376-0868>

Thomas Lauvaux  <https://orcid.org/0000-0002-7697-742X>

## References

- Al-mulali U 2014 Investigating the impact of nuclear energy consumption on GDP growth and CO<sub>2</sub> emission: a panel data analysis *Prog. Nucl. Energy* **73** 172–8
- Amin A, Altinoz B and Dogan E 2020 Analyzing the determinants of carbon emissions from transportation in European countries: the role of renewable energy and urbanization *Clean Technol. Environ. Policy* **22** 1725–34
- Amirnejad H and Kordi M A 2014 The group examined the relationship between air pollution, GDP, energy intensity and openness in Iran (applications of environmental Kuznets hypothesis) *J. Agric. Econ.* **8** 117–32
- Andres R J, Gregg J S, Losey L, Marland G and Boden T A 2011 Monthly, global emissions of carbon dioxide from fossil fuel consumption *Tellus B* **63** 309–27
- Balakrishnan K et al 2019 The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: the global burden of disease study 2017 *Lancet Planet. Health* **3** e26–39
- Bernard M and Ravenhill J 1994 Beyond product cycles and flying geese: regionalization, hierarchy, and the industrialization of East Asia *World Pol.* **47** 171–209
- Bilgili F, Koçak E and Bulut Ü 2016 The dynamic impact of renewable energy consumption on CO<sub>2</sub> emissions: a revisited environmental Kuznets curve approach *Renew. Sustain. Energy Rev.* **54** 838–45
- Boersma K F et al 2011 An improved tropospheric NO<sub>2</sub> column retrieval algorithm for the ozone monitoring instrument *Atmos. Meas. Tech.* **4** 1905–28
- Buehn A and Farzanegan M R 2013 Hold your breath: a new index of air pollution *Energy Econ.* **37** 104–13
- Cole M A 2000 Air pollution and ‘dirty’ industries: how and why does the composition of manufacturing output change with economic development? *Environ. Resour. Econ.* **17** 109–23
- Creutzig F and He D 2009 Climate change mitigation and co-benefits of feasible transport demand policies in Beijing *Transp. Res. D* **14** 120–31
- Dinda S, Coondoo D and Pal M 2000 Air quality and economic growth: an empirical study *Ecol. Econ.* **34** 409–23
- Dong F, Yu B and Pan Y 2019 Examining the synergistic effect of CO<sub>2</sub> emissions on PM<sub>2.5</sub> emissions reduction: evidence from China *J. Cleaner Prod.* **223** 759–71
- EPA 2007 Lists of potential control measures for PM<sub>2.5</sub> and precursors ([https://www3.epa.gov/ttn/naaqs/aqmguide/collection/cp2/20070607\\_harnett\\_pm2.5\\_control\\_measures.pdf](https://www3.epa.gov/ttn/naaqs/aqmguide/collection/cp2/20070607_harnett_pm2.5_control_measures.pdf))
- Giles-Corti B, Foster S, Shilton T and Falconer R 2010 The co-benefits for health of investing in active transportation *N S W Public Health Bull.* **21** 122–7
- Gouveia N, Hernández A, Cortínez O’Ryan A, Rodríguez D, Texcalac J, J T G, L B, L M, R M and X W 2019 Ambient PM<sub>2.5</sub> in Latin American cities: population exposure, trends, associated urban factors, and effects on mortality *Environ. Epidemiol.* **3** 139
- Green M, Kondragunta S, Ciren P and Xu C 2009 Comparison of GOES and MODIS aerosol optical depth (AOD) to aerosol robotic network (AERONET) AOD and IMPROVE PM<sub>2.5</sub> mass at Bondville, Illinois *J. Air Waste Manage. Assoc.* **59** 1082–91
- Grigg J 2002 The health effects of fossil fuel derived particles *Arch. Dis. Child.* **86** 79–83
- Guo X, Shi J, Ren D, Ren J and Liu Q 2017 Correlations between air pollutant emission, logistic services, GDP, and urban population growth from vector autoregressive modeling: a case study of Beijing *Nat. Hazards* **87** 885–97
- Gurney K R, Razlivanov I, Song Y, Zhou Y, Benes B and Abdul-Massih M 2012 Quantification of fossil fuel CO<sub>2</sub> emissions on the building/street scale for a large US city *Environ. Sci. Technol.* **46** 12194–202
- Hakkarainen J, Ialongo I, Maksyutov S and Crisp D 2018 Global XCO<sub>2</sub> anomalies as seen by Orbiting Carbon Observatory-2 *Atmos. Chem. Phys. Discuss.* (<https://doi.org/10.5194/acp-2018-649>)
- Hannesson R 2009 Energy and GDP growth *Int. J. Energy Sector Manag.* **3** 157–70
- Hatzigeorgiou E, Polatidis H and Haralambopoulos D 2011 CO<sub>2</sub> emissions, GDP and energy intensity: a multivariate cointegration and causality analysis for Greece, 1977–2007 *Appl. Energy* **88** 1377–85
- He K, Lei Y, Pan X, Zhang Y, Zhang Q and Chen D 2010 Co-benefits from energy policies in China *Energy* **35** 4265–72
- Hu Z and Rao K R 2009 Particulate air pollution and chronic ischemic heart disease in the eastern United States: a county level ecological study using satellite aerosol data *Environ. Health* **8** 26
- Inness A et al 2019 The CAMS reanalysis of atmospheric composition *Atmos. Chem. Phys.* **19** 3515–56
- Ishida H 2013 Causal relationship between fossil fuel consumption and economic growth in Japan: a multivariate approach *Int. J. Energy Econ. Policy* **3** 127–36
- Jalil A and Mahmud S F 2009 Environment Kuznets curve for CO<sub>2</sub> emissions: a cointegration analysis for China *Energy Policy* **37** 5167–72
- Janssens-Maenhout G, Crippa M, Guizzardi D, Dentener F, Muntean M, Pouliot G, Keating T, Zhang Q, Kurokawa J and Wankmüller R 2015 HTAP\_v2.2: a mosaic of regional and global emission grid maps for 2008 and 2010 to study hemispheric transport of air pollution *Atmos. Chem. Phys.* **15** 11411–32
- Jean-Baptiste P and Ducroux R 2003 Energy policy and climate change *Energy Policy* **31** 155–66
- Jiang Z, McDonald B C, Worden H, Worden J R and Boersma K F 2018 Unexpected slowdown of US pollutant emission reduction in the past decade *Proc. Natl Acad. Sci. USA* **115** 201801191
- Kaufmann R K, Davidsdottir B, Garnham S and Pauly P 1998 The determinants of atmospheric SO<sub>2</sub> concentrations: reconsidering the environmental Kuznets curve *Ecol. Econ.* **25** 209–20
- Kumar N 2010 What can affect AOD—PM<sub>2.5</sub> association? *Environ. Health Perspect.* **118** A109–10
- Kuznets S 1955 Economic growth and income inequality *Am. Econ. Rev.* **45** 1–28
- Lauvaux T et al 2016 High-resolution atmospheric inversion of urban CO<sub>2</sub> emissions during the dormant season of the Indianapolis flux experiment (INFLUX): urban inversion *J. Geophys. Res. Atmos.* **121** 5213–36
- Levy R and Hsu C 2015 MODIS Atmosphere L2 Aerosol Product. NASA MODIS Adaptive Processing System (USA: Goddard Space Flight Center) ([https://doi.org/10.5067/MODIS/MOD04\\_L2.006](https://doi.org/10.5067/MODIS/MOD04_L2.006))
- Li J, Song H and Geng D 2008 Causality relationship between coal consumption and GDP: difference of major OECD and non-OECD countries *Appl. Energy* **85** 421–9
- Li M, Zhang Q, Kurokawa J, Woo J-H, He K, Lu Z, Ohara T, Song Y, Streets D G and Carmichael G R 2017 MIX: a mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP *Atmos. Chem. Phys.* **17** 935–63
- Li Z and He X 2018 Analyzing the relationship between aerosol optical depth and GDP in China by integrating MODIS and nighttime light data 2018 7th Int. Conf. on Agro-Geoinformatics (Agro-Geoinformatics) (IEEE) pp 1–6
- Lin C-K, Chen T, Li X, De Marcellis-Warin N, Zigler C and Christiani D C 2019a Are per capita carbon emissions predictable across countries? *J. Environ. Manage.* **237** 569–75
- Lin C-K, Lin R-T, Chen P-C, Wang P, De Marcellis-Warin N, Zigler C and Christiani D C 2018 A global perspective on sulfur oxide controls in coal-fired power plants and cardiovascular disease *Sci. Rep.* **8** 2611

- Lin C-K, Lin R-T, Chen T, Zigler C, Wei Y and Christiani D C 2019b A global perspective on coal-fired power plants and burden of lung cancer *Environ Health* **18** 9
- Lioussé C, Assamoi E, Criqui P, Granier C and Rosset R 2014 Explosive growth in African combustion emissions from 2005 to 2030 *Environ. Res. Lett.* **9** 035003
- Lotfalipour M R, Falahi M A and Ashena M 2010 Economic growth, CO<sub>2</sub> emissions, and fossil fuels consumption in Iran *Energy* **35** 5115–20
- Lozano S and Gutierrez E 2008 Non-parametric frontier approach to modelling the relationships among population, GDP, energy consumption and CO<sub>2</sub> emissions *Ecol. Econ.* **66** 687–99
- Lu Q, Zheng J, Ye S, Shen X, Yuan Z and Yin S 2013 Emission trends and source characteristics of SO<sub>2</sub>, NO<sub>x</sub>, PM<sub>10</sub> and VOCs in the Pearl River Delta region from 2000 to 2009 *Atmos. Environ.* **76** 11–20
- Maione M, Fowler D, Monks P S, Reis S, Rudich Y, Williams M L and Fuzzi S 2016 Air quality and climate change: designing new win-win policies for Europe *Environ. Sci. Policy* **65** 48–57
- Maksyutov S, Takagi H, Valsala V K, Saito M, Oda T, Saeki T, Belikov D A, Saito R, Ito A and Yoshida Y 2013 Regional CO<sub>2</sub> flux estimates for 2009–2010 based on GOSAT and ground-based CO<sub>2</sub> observations *Atmos. Chem. Phys.* **13** 9351–73
- Mao X Q, Zeng A, Hu T, Xing Y K, Zhou J and Liu Z Y 2014 Co-control of local air pollutants and CO<sub>2</sub> from the Chinese coal-fired power industry *J. Cleaner Prod.* **67** 220–7
- Markandya A, Sampedro J, Smith S J, Van Dingenen R, Pizarro-Irizar C, Arto I and González-Eguino M 2018 Health co-benefits from air pollution and mitigation costs of the Paris agreement: a modelling study *Lancet Planet. Health* **2** e126–33
- Mayrhofer J P and Gupta J 2016 The science and politics of co-benefits in climate policy *Environ. Sci. Policy* **57** 22–30
- Meng W, Zhong Q, Yun X, Zhu X, Huang T, Shen H, Chen Y, Chen H, Zhou F and Liu J 2017 Improvement of a global high-resolution ammonia emission inventory for combustion and industrial sources with new data from the residential and transportation sectors *Environ. Sci. Technol.* **51** 2821–9
- Mosteller D 2016 Air pollution's hazy future in South Korea (available at: <https://datadrivenlab.org/air-quality-2/air-pollutions-hazy-future-in-south-korea-2/>) (Accessed 4 January 2020)
- Muller N Z 2014 Boosting GDP growth by accounting for the environment *Science* **345** 873–4
- Natural Resources Canada 2020 Crude oil facts (available at: <https://www.nrcan.gc.ca/science-data/data-analysis/energy-data-analysis/energy-facts/crude-oil-facts/20064#L6>) (Accessed 4 January 2020)
- Newman P 2017 Decoupling economic growth from fossil fuels *Modern Econ.* **8** 791–805
- NOAA 2018 NOAA's greenhouse gas index up 41 percent since 1990 (available at: <https://research.noaa.gov/article/ArtMid/587/ArticleID/2359/NOAA%E2%80%99s-greenhouse-gas-index-up-41-percent-since-1990>) (Accessed 4 January 2020)
- Oda T, Maksyutov S and Andres R J 2018 The open-source data inventory for anthropogenic carbon dioxide (CO<sub>2</sub>), version 2016 (ODIAC2016): a global, monthly fossil-fuel CO<sub>2</sub> gridded emission data product for tracer transport simulations and surface flux inversions *Earth Syst. Sci. Data* **10** 87
- Pao H-T and Tsai C-M 2011 Multivariate Granger causality between CO<sub>2</sub> emissions, energy consumption, FDI (foreign direct investment) and GDP (gross domestic product): evidence from a panel of BRIC (Brazil, Russian Federation, India, and China) countries *Energy* **36** 685–93
- Pata U K 2020 Renewable and non-renewable energy consumption, economic complexity, CO<sub>2</sub> emissions, and ecological footprint in the USA: testing the EKC hypothesis with a structural break *Environ. Sci. Pollut. Res.* (<https://doi.org/10.1007/s11356-020-10446-3>)
- Payne J E 2011 US disaggregate fossil fuel consumption and real GDP: an empirical note *Energy Sources B* **6** 63–68
- Pope C A, Thun M J, Namboodiri M M, Dockery D W, Evans J S, Speizer F E and Heath C W 1995 Particulate air pollution as a predictor of mortality in a prospective study of US adults *Am. J. Respir. Crit. Care Med.* **151** 669–74
- Raupach M R, Marland G, Ciais P, Le Quééré C, Canadell J G, Klepper G and Field C B 2007 Global and regional drivers of accelerating CO<sub>2</sub> emissions *Proc. Natl Acad. Sci.* **104** 10288–93
- Renzhi N and Baek Y J 2020 Can financial inclusion be an effective mitigation measure? evidence from panel data analysis of the environmental Kuznets curve *Finance Res. Lett.* **101725**
- Saboori B, Sulaiman J B and Mohd S 2012 An empirical analysis of the environmental Kuznets curve for CO<sub>2</sub> emissions in Indonesia: the role of energy consumption and foreign trade *Int. J. Econ. Finance* **4** 243–51
- Silva S J and Arellano A F 2017 Characterizing regional-scale combustion using satellite retrievals of CO, NO<sub>2</sub> and CO<sub>2</sub> *Remote Sens.* **9** 744
- Soriano J B et al 2020 Prevalence and attributable health burden of chronic respiratory diseases, 1990–2017: a systematic analysis for the global burden of disease study 2017 *Lancet Respir. Med.* **8** 585–96
- Tan Q, Wen Z and Chen J 2016 Goal and technology path of CO<sub>2</sub> mitigation in China's cement industry: from the perspective of co-benefit *J. Cleaner Prod.* **114** 299–313
- Thakrar S K et al 2020 Reducing mortality from air pollution in the United States by targeting specific emission sources *Environ. Sci. Technol. Lett.* **7** 639–45
- Tiwari A K 2011 A structural VAR analysis of renewable energy consumption, real GDP and CO<sub>2</sub> emissions: evidence from India *Econ. Bull.* **31** 1793–806
- Transportpolicy 2012 China: air quality standards (available at: <https://www.transportpolicy.net/standard/china-air-quality-standards/>) (Accessed 4 January 2020)
- Tucker M 1995 Carbon dioxide emissions and global GDP *Ecol. Econ.* **15** 215–23
- UNFCCC 2015 Paris agreement to the United Nations framework convention on climate change (<https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>)
- Usama A, Solarin S A and Salahuddin M 2020 The prominence of renewable and non-renewable electricity generation on the environmental Kuznets curve: a case study of Ethiopia *Energy* **211** 118665
- Veefkind J P, Aben I, McMullan K, Förster H, De Vries J, Otter G, Claas J, Eskes H J, De Haan J F and Kleipool Q 2012 TROPOMI on the ESA Sentinel-5 precursor: a GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications *Remote Sens. Environ.* **120** 70–83
- Vural G 2020 How do output, trade, renewable energy and non-renewable energy impact carbon emissions in selected Sub-Saharan African countries? *Resour. Policy* **69** 101840
- West J J, Smith S J, Silva R A, Naik V, Zhang Y, Adelman Z, Fry M M, Anenberg S, Horowitz L W and Lamarque J-F 2013 Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health *Nat. Clim. Change* **3** 885–9
- Wong S L, Chang Y and Chia W-M 2013 Energy consumption, energy R&D and real GDP in OECD countries with and without oil reserves *Energy Econ.* **40** 51–60
- Workman A, Blashki G, Bowen K J, Karoly D J and Wiseman J 2018 The political economy of health co-benefits: embedding health in the climate change agenda *Int. J. Environ. Res. Public Health* **15** 674
- Xiao Q, Ma Z, Li S and Liu Y 2015 The impact of winter heating on air pollution in China *PLoS One* **10** e0117311
- Xie Y, Wang Y, Zhang K, Dong W, Lv B and Bai Y 2015 Daily estimation of ground-level PM<sub>2.5</sub> concentrations over

- Beijing using 3 km resolution MODIS AOD *Environ. Sci. Technol.* **49** 12280–8
- Ye X, Lauvaux T, Kort E A, Oda T, Feng S, Lin J C, Yang E G and Wu D 2020 Constraining fossil fuel CO<sub>2</sub> emissions from urban area using OCO-2 observations of total column CO<sub>2</sub> *J. Geophys. Res. Atmos.* **125** e2019JD030528
- Yin P et al 2020 The effect of air pollution on deaths, disease burden, and life expectancy across China and its provinces, 1990–2017: an analysis for the global burden of disease study 2017 *Lancet Planet. Health* **4** e386–98
- You W, Zang Z, Zhang L, Li Y, Pan X and Wang W 2016 National-scale estimates of ground-level PM<sub>2.5</sub> concentration in China using geographically weighted regression based on 3 km resolution MODIS AOD *Remote Sens.* **8** 184
- Zhao D, Xin J, Gong C, Wang X, Ma Y and Ma Y 2018 Trends of aerosol optical properties over the heavy industrial zone of Northeastern Asia in the past decade (2004–15) *J. Atmos. Sci.* **75** 1741–54
- Zhao Y, Zhang J and Nielsen C 2013 The effects of recent control policies on trends in emissions of anthropogenic atmospheric pollutants and CO<sub>2</sub> in China *Atmos. Chem. Phys.* **13** 487–508
- Zheng B, Chevallier F, Ciais P, Broquet G, Wang Y, Lian J and Zhao Y 2020 *Atmos. Chem. Phys.* **20** 8501–10