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Country-scale trends in air pollution and fossil fuel CO₂ emissions during 2001–2018: confronting the roles of national policies and economic growthRuixue Lei¹ , Sha Feng¹ and Thomas Lauvaux^{1,2} ¹ Department of Meteorology and Atmospheric Science, The Pennsylvania State University, University Park, PA 16802, United States of America² 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**Keywords:** fossil fuel CO₂, 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 (CO₂) and pollutants in the atmosphere. Based on 18 years (2001–2018) of aerosol optical depth (AOD) data from Moderate Resolution Imaging Spectroradiometer satellite, FFCO₂ 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_{2.5} and NO₂ over urbanized areas shows that the pollutants leading to the AOD load can vary significantly by country. A strong connection between GDP and FFCO₂ 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 (CO₂) 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 (FFCO₂) remains by far the largest contributor to AGGI. In response to the rapid increase in atmospheric CO₂ 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 CO₂ 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 CO₂ 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 FFCO₂ 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 FFCO₂ 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 CO₂ (e.g. OCO-2/3, GOSAT-2), FFCO₂ 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 FFCO₂ emissions over various countries have been based primarily on inventory estimates rather than direct measurements (e.g. NO₂ over the US (Jiang et al 2018)).

The correlation and causality between CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions at the same time, decoupling CO₂ 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 CO₂ 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), SO₂ (Kaufmann et al 1998, Cole 2000, Dinda et al 2000, Buehn and Farzanegan 2013, Lu et al 2013, Guo et al 2017) and NO_x (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, FFCO₂ 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, FFCO₂ 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, FFCO₂ 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, FFCO₂ 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 XCO₂ measurements, we used the global monthly FFCO₂ 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 FFCO₂ emission. ODIAC has been applied by the international research communities for a wide range of research, like CO₂ 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 FFCO₂ 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⁻² d⁻¹ (C = Carbon) FF emission mask to select urbanized areas of a given country where anthropogenic sources dominate the observed enhancements and exclude the other CO₂ 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, FFCO₂ emission, PM_{2.5} and NO₂) in the following analysis are filtered by 0.1 g C m⁻² d⁻¹ 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), FFCO₂ 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_{2.5} (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 FFCO₂ emissions are greater than 0.1 g C m⁻² d⁻¹. Both the annual mean and trend of AOD may vary with the different emission masks. We examined in detail the effect of our high-FFCO₂ emission mask threshold in figure S2 for large countries like China, the USA, and India.

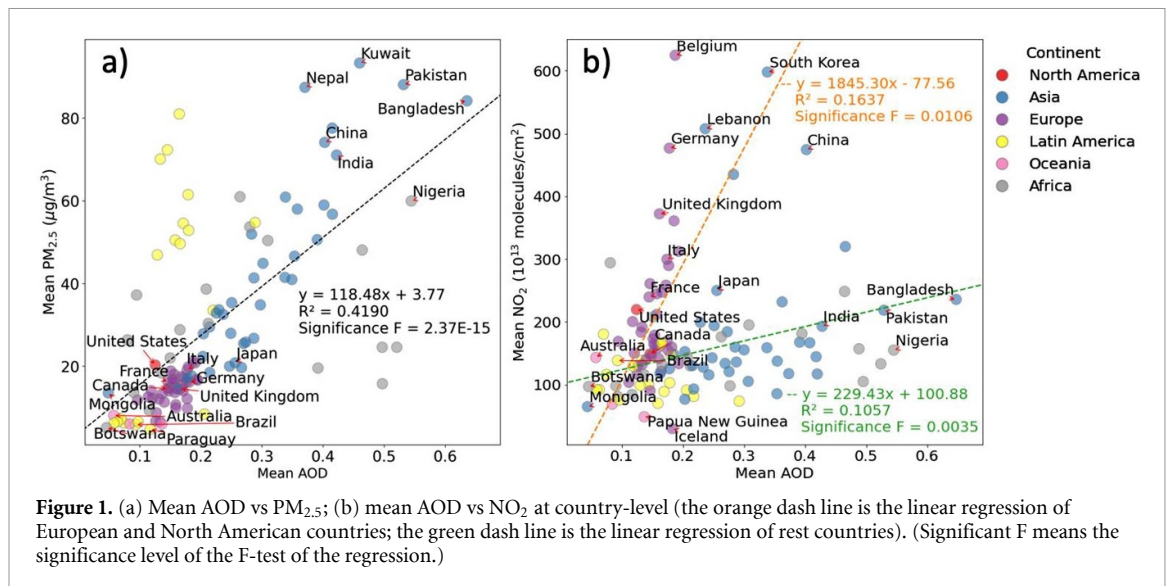
Note that the drivers of air pollution vary across countries. A signal proxy may not represent the entire array of air pollutants. Thus, we compared AOD with PM_{2.5} and NO₂, two major pollutants from various anthropogenic sources, to examine the primary drivers of AOD across countries. The major anthropogenic sources of PM_{2.5} originate from the industrial and commercial, transportation, food and agriculture, and the residential sectors, while anthropogenic NO₂ emissions are mainly from industrial and commercial, and transportation sectors (Thakrar *et al* 2020). The monthly 0.25° × 0.25° global PM_{2.5} was obtained from CAMS global reanalysis (Inness *et al* 2019). Monthly 0.125° × 0.125° global tropospheric NO₂ was from the OMI (Boersma *et al* 2011). Note that PM_{2.5} started available from 2003 and NO₂ started available from 2005, we therefore selected AOD vs PM_{2.5} in 2003–2018 and AOD vs NO₂ in 2005–2018 for comparison. Similar to AOD, the original monthly PM_{2.5} and NO₂ are re-gridded to 1° × 1° before calculation of annual means, then the same 0.1 g C m⁻² d⁻¹ FFCO₂ emission mask was applied to the country-level annual means for the comparison.

We studied the relationship between AOD, FFCO₂ 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 FFCO₂ emissions across countries of various sizes and carbon intensities, we used GDP per capita and FFCO₂ 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 FFCO₂ emissions and GDP at the country-level, in terms of annual mean and growth rate. The linear regression between the mean GDP and FFCO₂ 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 FFCO₂ 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 FFCO₂ growth rates corresponding to fast-growing economies, the major European countries and the United States fall in the increasing-GDP-and-decreasing-FFCO₂-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 FFCO₂ emission growth, as the result of their major industries being tourism and agriculture

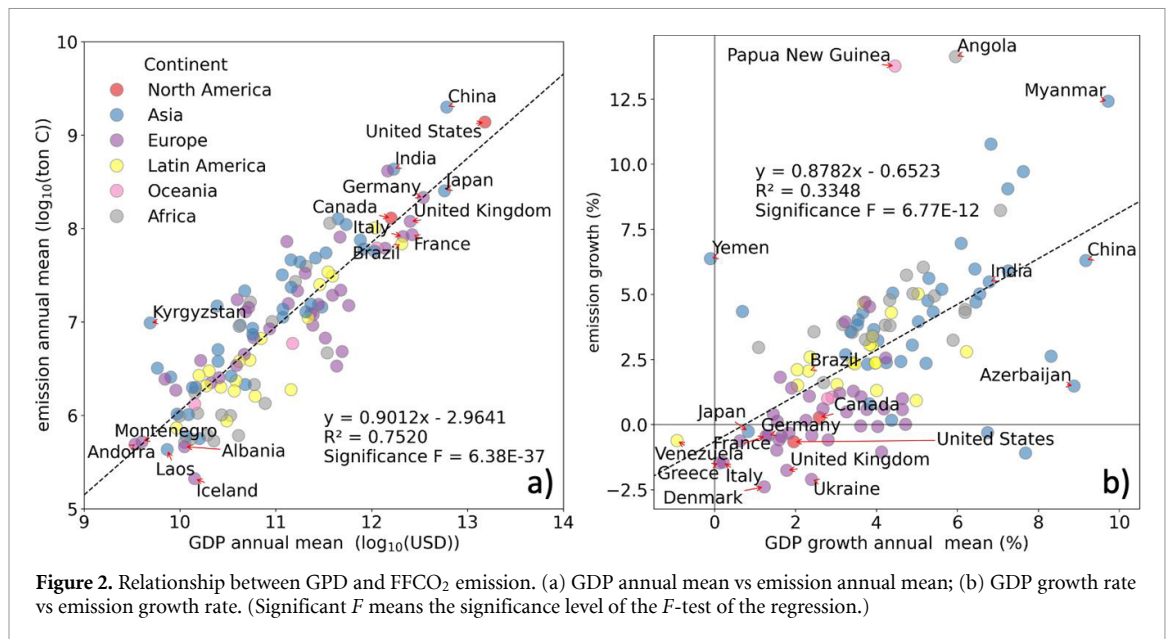


Figure 2. Relationship between GDP and FFCO₂ emission. (a) GDP annual mean vs emission annual mean; (b) GDP growth rate vs emission growth rate. (Significant *F* means the significance level of the *F*-test of the regression.)

instead of heavily relying on carbon energy sources.

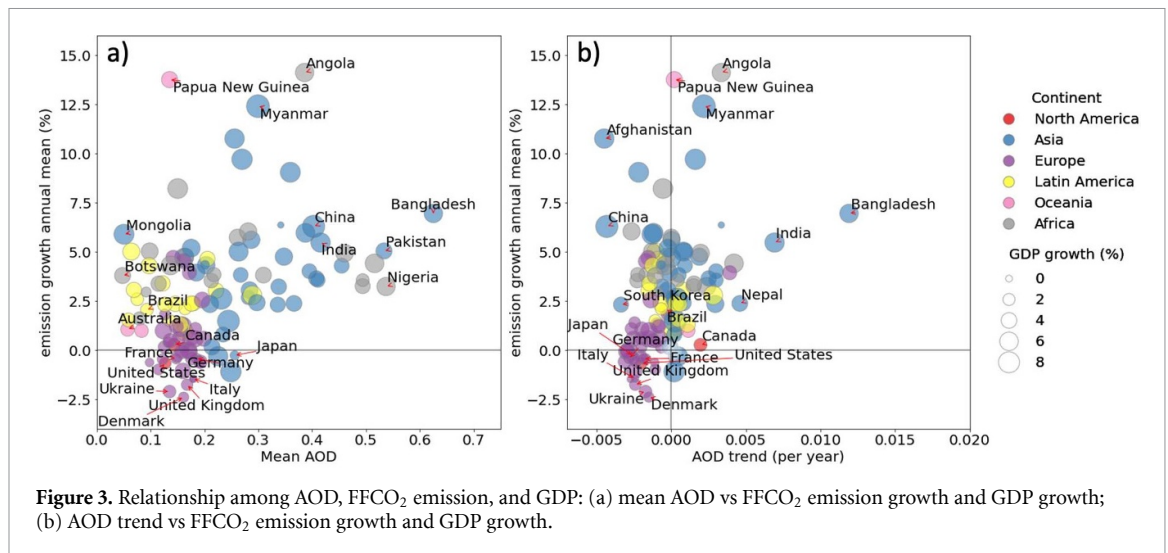
3.3. Relationship of air pollution vs fossil fuel consumption and economy

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 FFCO₂ 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 FFCO₂ emission growth, while the European and American countries are clustered showing low mean AOD and low FFCO₂ 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 FFCO₂ emission growth rates. On the other hand, fast-growing-developing countries, such as China, Indian, and Bangladesh, show high AOD and high FFCO₂ 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 FFCO₂ (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 FFCO₂ emission increase rates with a decreasing AOD trend. While Afghanistan may have too few data points after applying the 0.1 g C m⁻² d⁻¹ FFCO₂ 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 FFCO₂ 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



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 FFCO₂ 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, FFCO₂ 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_{2.5} that directly affects human health. PM_{2.5} is a better indicator of air pollution, but the country-level estimates of PM_{2.5} for the period of interest are not readily available. NO₂ is another indicator of air pollution, but the temporal coverage of OMI data is too short to examine long-term trends. Another high-resolution NO₂ 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 XCO₂ from GOSAT and OCO-2/3 could be a proxy of the climate response to the FF burning, but extracting the FF contribution from XCO₂ 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 CO₂ by using spatial XCO₂ anomaly along with the latitude band (Hakkarainen *et al* 2018), but the anomaly failed to reflect the local changes in FFCO₂ emission. In future studies, the combination of NO₂ retrievals

from TROPOMI and XCO₂ 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, FFCO₂ emission, and GDP. Although we applied 0.1 g C m⁻² d⁻¹ FFCO₂ emission mask to screen out AOD and CO₂ 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_{2.5} and NO₂ 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 NO₂/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 FFCO₂. For example, using more renewable energy may slow down the growth rate of, or even decrease, CO₂ 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 NO₂ from TROPOMI), more detailed investigation becomes feasible in the future.

We only studied the relationships among AOD, FFCO₂ 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 CO₂ 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, FFCO₂ 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_{2.5} and NO₂ over urbanized areas shows that the pollutants leading to the AOD load can vary significantly by country. Although AOD is correlated with PM_{2.5} for almost all countries, its linkage to NO₂ 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 FFCO₂ 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 FFCO₂ emission and negative AOD trends in recent two decades. Some developing countries, i.e. China, even maintained fast GDP and FFCO₂ 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/

NO₂ from OMI: https://www.temis.nl/airpollution/no2col/no2regioomimonth_qa.php

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

FFCO₂ emission from ODIAC: http://db.cger.nies.go.jp/dataset/ODIAC/DL_odiad2019.html

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

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