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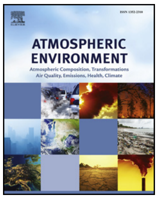

Socioeconomic and atmospheric factors affecting aerosol radiative forcing: Production-based versus consumption-based perspective

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ABSTRACT

There exist substantial differences in top-of-atmosphere direct radiative forcing of aerosols due to a region's economic production (RF_p) and consumption (RF_c), in the context of economic globalization, trade and globalizing air pollution. Yet an explicit systematic analysis of all socioeconomic and atmospheric factors determining the RF difference is lacking. Here, we evaluate five socioeconomic (population, per capita output, emission intensity) and atmospheric (chemical efficiency and radiative efficiency) factors that determine a region's RF_p, RF_c and their difference. We consider the RF of secondary inorganic aerosols, primary organic aerosols and black carbon by 10 regions worldwide in 2007. The population size varies by a factor of nine across the regions, and per capita output by 40 times from both production- and consumption-based perspectives. The cross-regional spread reaches a factor of 181 (species dependent) for production-based emission intensity and a factor of 96 for consumption-based intensity. From one region to another, production-based chemical efficiency changes within a factor of 5 and consumption-based efficiency within a factor of 3.5. Radiative efficiency varies slightly across the regions (within 2) from both production- and consumption-based perspectives. Although socioeconomic factors are often a greater driver for the difference between a source region's RF_p and RF_c, the atmospheric factors are also important for many source regions and species. Our results contribute to regional attribution of climate change and establishment of effective international collaborative mitigation strategies.

1. Introduction

Anthropogenic aerosols are the most important short-lived climate forcer modulating the warming effects of carbon dioxide (CO_2) and other greenhouse gases, in addition to their adverse effects on public health (Boucher et al., 2013; Myhre et al., 2013). Primary organic aerosols (POA), secondary organic aerosols (SOA) and secondary inorganic aerosols (SIOA, including sulfate, nitrate and ammonium) scatter solar radiation and exert a negative top-of-atmosphere direct radiative forcing (RF), whereas black carbon (BC) exerts strong absorption and a positive RF.

Anthropogenic aerosols and precursor gases (from which secondary aerosols are formed) are emitted as a byproduct of production of goods and services to supply consumption. Under the economic globalization, international trade has meant geographical (spatial) separation of production and consumption (Brizga et al., 2017; Copeland and Taylor, 2004; Fan et al., 2016; Geng et al., 2017; Kanemoto et al., 2014; Meng et al., 2016; Mi et al., 2016; Su and Ang, 2014; Tian et al., 2014; Weber and Matthews, 2007). Consumption in a region leads to direct emissions (e.g., by burning fossil fuels for driving and household heating) and, more often, requires economic production along the upstream supply chain that may occur outside that consuming region, with emissions as a byproduct. Emissions released by exporters of goods are largely associated with consumption in importers (Meng et al., 2015; Oita et al.,

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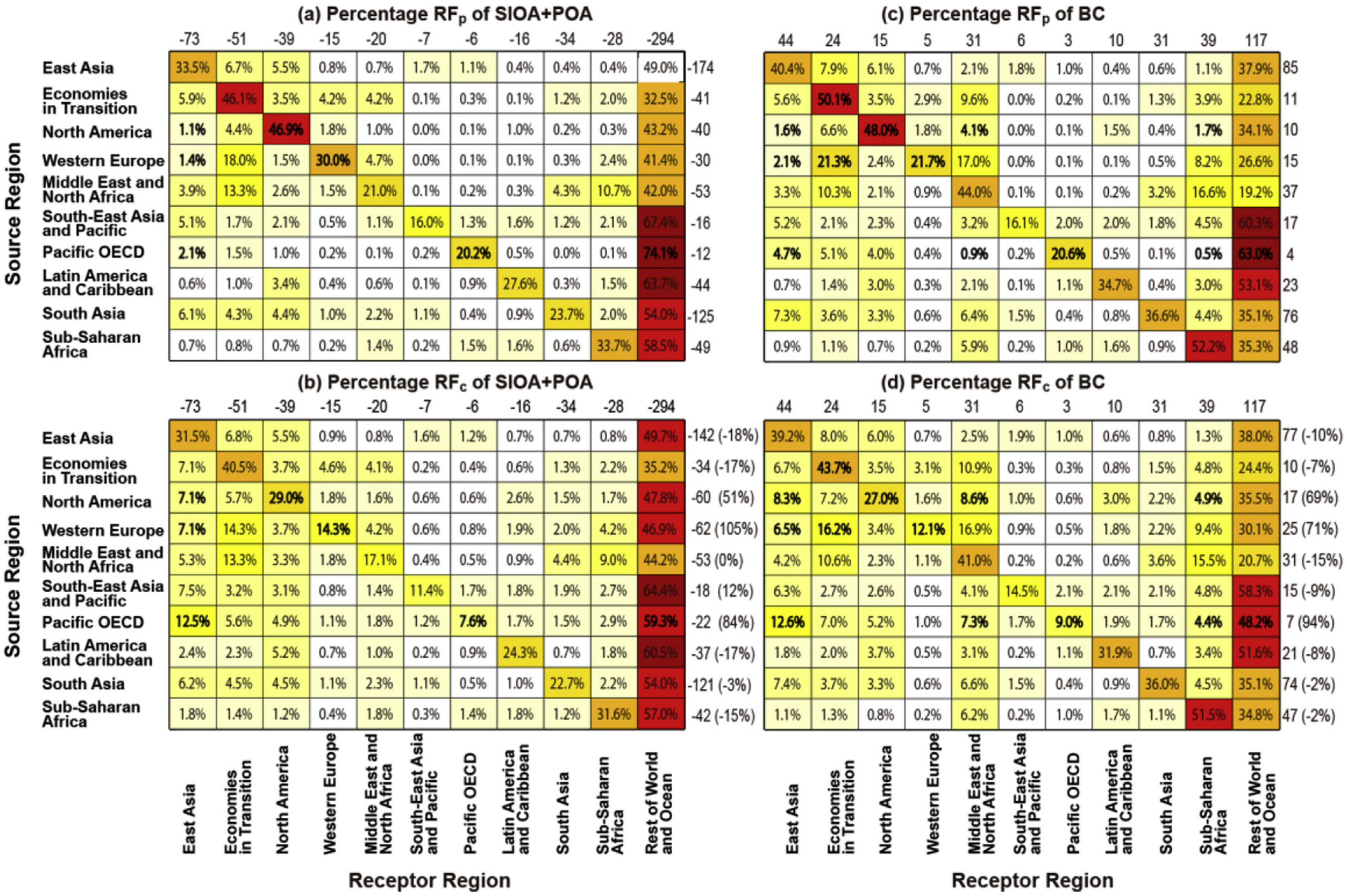

(a) Percentage RF_p of SIOA+POA

Source Region	East Asia	Economies in Transition	North America	Western Europe	Middle East and North Africa	South-East Asia and Pacific	Pacific OECD	Latin America and Caribbean	South Asia	Sub-Saharan Africa	Rest of World and Ocean	
	-73	-51	-39	-15	-20	-7	-6	-16	-34	-28	-294	
East Asia	33.5%	6.7%	5.5%	0.8%	0.7%	1.7%	1.1%	0.4%	0.4%	0.4%	49.0%	-174
Economies in Transition	5.9%	46.1%	3.5%	4.2%	4.2%	0.1%	0.3%	0.1%	1.2%	2.0%	32.5%	-41
North America	**1.1%**	4.4%	**46.9%**	1.8%	1.0%	0.0%	0.1%	1.0%	0.2%	0.3%	43.2%	-40
Western Europe	**1.4%**	18.0%	1.5%	**30.0%**	4.7%	0.0%	0.1%	0.1%	0.3%	2.4%	41.4%	-30
Middle East and North Africa	3.9%	13.3%	2.6%	1.5%	21.0%	0.1%	0.2%	0.3%	4.3%	10.7%	42.0%	-53
South-East Asia and Pacific	5.1%	1.7%	2.1%	0.5%	1.1%	16.0%	1.3%	1.6%	1.2%	2.1%	67.4%	-16
Pacific OECD	**2.1%**	1.5%	1.0%	0.2%	0.1%	0.2%	**20.2%**	0.5%	0.0%	0.1%	**74.1%**	-12
Latin America and Caribbean	0.6%	1.0%	3.4%	0.4%	0.6%	0.1%	0.9%	27.6%	0.3%	1.5%	63.7%	-44
South Asia	6.1%	4.3%	4.4%	1.0%	2.2%	1.1%	0.4%	0.9%	23.7%	2.0%	54.0%	-125
Sub-Saharan Africa	0.7%	0.8%	0.7%	0.2%	1.4%	0.2%	1.5%	1.6%	0.6%	33.7%	58.5%	-49

(b) Percentage RF_c of SIOA+POA

Source Region	East Asia	Economies in Transition	North America	Western Europe	Middle East and North Africa	South-East Asia and Pacific	Pacific OECD	Latin America and Caribbean	South Asia	Sub-Saharan Africa	Rest of World and Ocean	
	-73	-51	-39	-15	-20	-7	-6	-16	-34	-28	-294	
East Asia	31.5%	6.8%	5.5%	0.9%	0.8%	1.6%	1.2%	0.7%	0.7%	0.8%	49.7%	-142 (-18%)
Economies in Transition	7.1%	40.5%	3.7%	4.6%	4.1%	0.2%	0.4%	0.6%	1.3%	2.2%	35.2%	-34 (-17%)
North America	**7.1%**	5.7%	**29.0%**	1.8%	1.6%	0.6%	0.6%	2.6%	1.5%	1.7%	47.8%	-60 (51%)
Western Europe	**7.1%**	14.3%	3.7%	**14.3%**	4.2%	0.6%	0.8%	1.9%	2.0%	4.2%	46.9%	-62 (105%)
Middle East and North Africa	5.3%	13.3%	3.3%	1.8%	17.1%	0.4%	0.5%	0.9%	4.4%	9.0%	44.2%	-53 (0%)
South-East Asia and Pacific	7.5%	3.2%	3.1%	0.8%	1.4%	11.4%	1.7%	1.8%	1.9%	2.7%	64.4%	-18 (12%)
Pacific OECD	**12.5%**	5.6%	4.9%	1.1%	1.8%	1.2%	**7.6%**	1.7%	1.5%	2.9%	**59.3%**	-22 (84%)
Latin America and Caribbean	2.4%	2.3%	5.2%	0.7%	1.0%	0.2%	0.9%	24.3%	0.7%	1.8%	60.5%	-37 (-17%)
South Asia	6.2%	4.5%	4.5%	1.1%	2.3%	1.1%	0.5%	1.0%	22.7%	2.2%	54.0%	-121 (-3%)
Sub-Saharan Africa	1.8%	1.4%	1.2%	0.4%	1.8%	0.3%	1.4%	1.8%	1.2%	31.6%	57.0%	-42 (-15%)

(c) Percentage RF_p of BC

Source Region	East Asia	Economies in Transition	North America	Western Europe	Middle East and North Africa	South-East Asia and Pacific	Pacific OECD	Latin America and Caribbean	South Asia	Sub-Saharan Africa	Rest of World and Ocean	
	44	24	15	5	31	6	3	10	31	39	117	
East Asia	40.4%	7.9%	6.1%	0.7%	2.1%	1.8%	1.0%	0.4%	0.6%	1.1%	37.9%	85
Economies in Transition	5.6%	**50.1%**	3.5%	2.9%	9.6%	0.0%	0.2%	0.1%	1.3%	3.9%	22.8%	11
North America	**1.6%**	6.6%	**48.0%**	1.8%	**4.1%**	0.0%	0.1%	1.5%	0.4%	**1.7%**	34.1%	10
Western Europe	**2.1%**	**21.3%**	2.4%	**21.7%**	17.0%	0.0%	0.1%	0.1%	0.5%	8.2%	26.6%	15
Middle East and North Africa	3.3%	10.3%	2.1%	0.9%	44.0%	0.1%	0.1%	0.2%	3.2%	16.6%	19.2%	37
South-East Asia and Pacific	5.2%	2.1%	2.3%	0.4%	3.2%	16.1%	2.0%	2.0%	1.8%	4.5%	60.3%	17
Pacific OECD	**4.7%**	5.1%	4.0%	0.4%	**0.9%**	0.2%	**20.6%**	0.5%	0.1%	**0.5%**	**63.0%**	4
Latin America and Caribbean	0.7%	1.4%	3.0%	0.3%	2.1%	0.1%	1.1%	34.7%	0.4%	3.0%	53.1%	23
South Asia	7.3%	3.6%	3.3%	0.6%	6.4%	1.5%	0.4%	0.8%	36.6%	4.4%	35.1%	76
Sub-Saharan Africa	0.9%	1.1%	0.7%	0.2%	5.9%	0.2%	1.0%	1.6%	0.9%	52.2%	35.3%	48

(d) Percentage RF_c of BC

Source Region	East Asia	Economies in Transition	North America	Western Europe	Middle East and North Africa	South-East Asia and Pacific	Pacific OECD	Latin America and Caribbean	South Asia	Sub-Saharan Africa	Rest of World and Ocean	
	44	24	15	5	31	6	3	10	31	39	117	
East Asia	39.2%	8.0%	6.0%	0.7%	2.5%	1.9%	1.0%	0.6%	0.8%	1.3%	38.0%	77 (-10%)
Economies in Transition	6.7%	**43.7%**	3.5%	3.1%	10.9%	0.3%	0.3%	0.8%	1.5%	4.8%	24.4%	10 (-7%)
North America	**8.3%**	7.2%	**27.0%**	1.6%	**8.6%**	1.0%	0.6%	3.0%	2.2%	**4.9%**	35.5%	17 (69%)
Western Europe	**6.5%**	**16.2%**	3.4%	**12.1%**	16.9%	0.9%	0.5%	1.8%	2.2%	9.4%	30.1%	25 (71%)
Middle East and North Africa	4.2%	10.6%	2.3%	1.1%	41.0%	0.2%	0.2%	0.6%	3.6%	15.5%	20.7%	31 (-15%)
South-East Asia and Pacific	6.3%	2.7%	2.6%	0.5%	4.1%	14.5%	2.1%	2.1%	2.1%	4.8%	58.3%	15 (-9%)
Pacific OECD	**12.6%**	7.0%	5.2%	1.0%	**7.3%**	1.7%	**9.0%**	1.9%	1.7%	**4.4%**	**48.2%**	7 (94%)
Latin America and Caribbean	1.8%	2.0%	3.7%	0.5%	3.1%	0.2%	1.1%	31.9%	0.7%	3.4%	51.6%	21 (-8%)
South Asia	7.4%	3.7%	3.3%	0.6%	6.6%	1.5%	0.4%	0.9%	36.0%	4.5%	35.1%	74 (-2%)
Sub-Saharan Africa	1.1%	1.3%	0.8%	0.2%	6.2%	0.2%	1.0%	1.7%	1.1%	51.5%	34.8%	47 (-2%)

Fig. 1. Radiative forcing (RF_p and RF_c) exerted by each source region upon each receptor region. The percentage values in each table denote the portions of forcing exerted upon each receptor region (i.e., summation across all receptor regions leads to 100%). The numbers outside each table denote the total forcing (10^{-3} W/m^2) exerted by each source region (vertical) or upon each receptor region (horizontal). The percentage values in parentheses in the lower panels denote the relative change from RF_p to RF_c.

2016; Takahashi et al., 2014; Yang et al., 2017; Zhang and Lin, 2018; Zhao et al., 2016). For example, China is a “world factory” that supplies global consumption, and up to one third of its emissions are related to its export production (Arce et al., 2016; Guan et al., 2014b; Lin et al., 2014; Su and Ang, 2014; Wang et al., 2017; Zhao et al., 2015). Such trade-embedded relocation of emissions also means a large difference between aerosol RF caused by a region's production (Li et al., 2016) and the RF caused by its consumption, a critical issue in climate change attribution raised recently (Lin et al., 2016).

Atmospheric processes govern the fate and RF of aerosols in the air (Fairlie et al., 2007; Li et al., 2014). Unlike CO_2, the regional and global RF exerted by a unit of emission of aerosols or precursor gases greatly depends on where the emission is released and how the aerosol is situated in the atmosphere (HTAP, 2010). For instance, the efficiency of absorbing aerosols depends on its height relative to clouds and mixing with scattering aerosols (Lin et al., 2012). Relative humidity affects the efficiency of scattering aerosols due to their hygroscopicity (Fierz-Schmidhauser et al., 2010). Furthermore, dry air means weak wet scavenging of aerosols so that aerosols can stay in the atmosphere longer to be carried to higher altitudes and further distances (Jimenez et al., 2009; Yu et al., 2012). As an updated study upon Hemispheric Transport of Air Pollution (HTAP, 2010), Stjern et al. (2016) examined the RF of sulfate (SO_4), POA and BC per unit of pollutants emitted from six major source regions in the northern hemisphere simulated by 10 global models. They found that a 20% emission reduction in South and East Asia have distinctive impacts on the radiative budget over individual receptor regions, especially for the impacts of BC emission reduction.

The complex socioeconomic-atmospheric process involved in the RF of aerosols and each region's role as a consumer versus a producer means that delineating these socioeconomic and atmospheric factors is critical for regional attribution of climate change and for establishment of effective international collaborative mitigation strategies. Although our recent work (Lin et al., 2016) has differentiated regions' production-based from consumption-based aerosol RF, the individual socioeconomic and atmospheric factors leading to such RF differences have not been explicitly quantified.

Building upon Lin et al. (2016), here we explicitly quantify the five socioeconomic (related to emissions) and atmospheric (related to chemical, transport and radiative processes) factors that determine the aerosol RF contributed by a region's production and consumption. The difference between consumption-based (RF_c) and production-based (RF_p) forcing can be rationalized by examining these factors. To be more specific, we quantify the driving factors for top-of-atmosphere direct RF of SIOA, POA and BC in 2007. Following Lin et al. (2016), we examine RF contributed by 11 regions across the globe (see their Fig. S1 for regional maps), including East Asia (China, Mongolia, and North Korea), Economies in Transition (Eastern Europe and Former Soviet Union), North America (the United States and Canada), Western Europe, Middle East and North Africa, Southeast Asia and Pacific, Pacific OECD (Japan, South Korea, Australia, and New Zealand), Latin America and Caribbean, South Asia, Sub-Saharan Africa, and Rest of the World (Greenland and Antarctic).

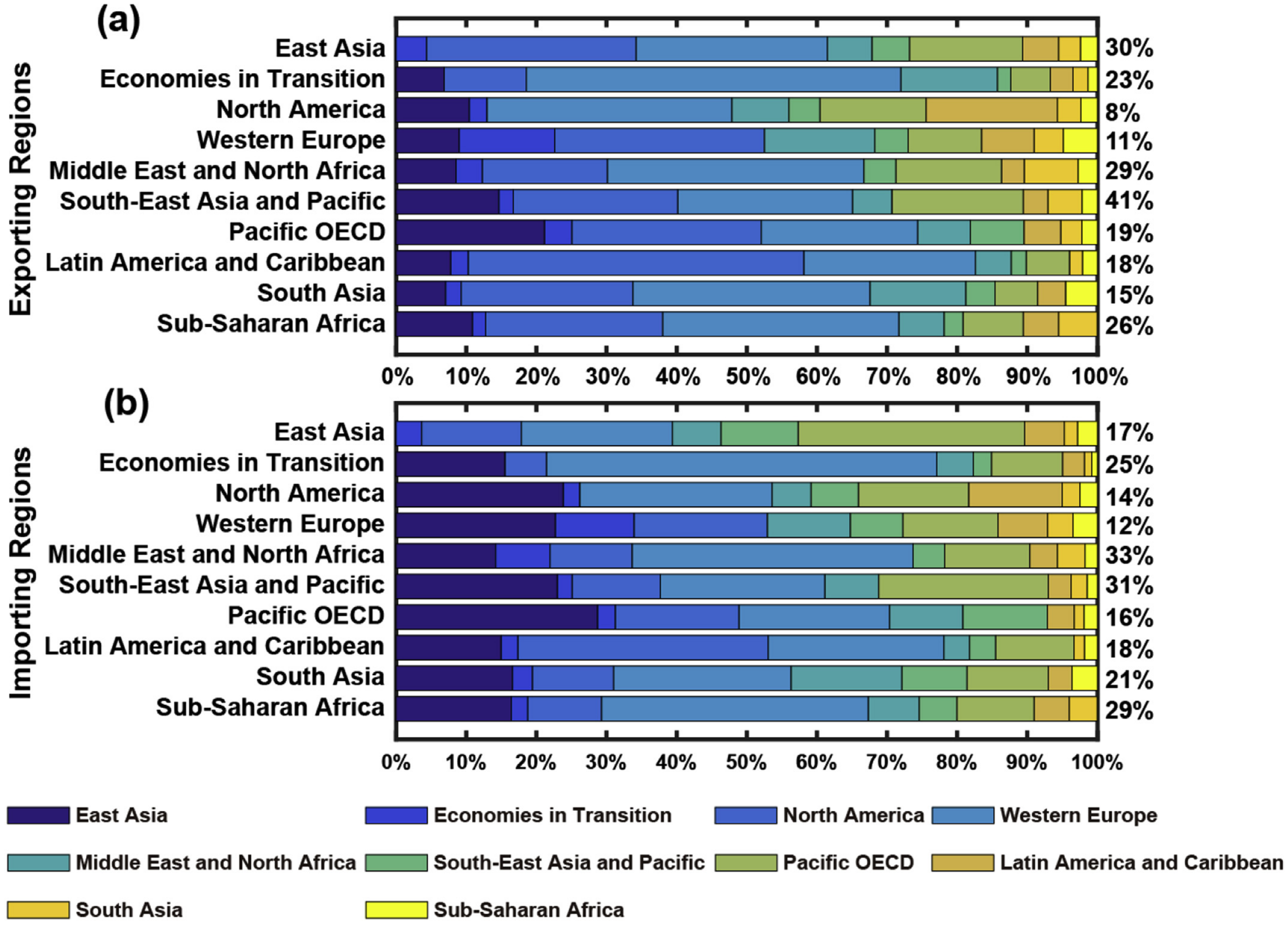

Fig. 2. Percentage share of export and import triggered monetary output in total monetary output. (a) Percentage share of export triggered monetary output of an exporting region among its nine destination regions (importers, horizontal bars) in 2007. The bolded number for each exporting region denotes the percentage share of that region's export triggered monetary output in its total production triggered output. (b) Percentage share of import triggered monetary output of an importing region among its nine source regions (exporters, horizontal bars) in 2007. The bolded number for each importing region denotes the percentage share of that region's import triggered monetary output in its total consumption output.

2. Quantification of aerosol radiative forcing and driving factors

2.1. Calculation of radiative forcing

Calculations of RF_p and RF_c are described in Lin et al. (2016). Briefly, the top-of-atmosphere direct RF of individual aerosols (SIOA, POA, and BC) contributed by each region in 2007 is derived from five steps. (Unless stated otherwise, the top-of-atmosphere direct RF is referred to as RF hereafter.) First, a country-specific inventory of anthropogenic production-based emissions (i.e., those physically released from a region, E_p) is built. This inventory includes sulfur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO), ammonia (NH_3), POA, and BC. Second, a consumption-based emission (E_c) inventory is derived by integrating E_p and a global multi-regional input-output table (GTAP8) (Narayanan et al., 2012) that accounts for inter-sectoral dependence and supply chain of the global economy. Third, these country-specific emission inventories are projected on a longitude-latitude grid to drive subsequent atmospheric simulations. Fourth, 24 sensitivity simulations of a chemical transport model (GEOS-Chem) are conducted to quantify the aerosol loading due to global emissions, E_p for each of the 11 regions, or E_c for each region. SIOA are formed chemically from emitted SO_2, NO_X and NH_3. Finally, 70 simulations of a radiative transfer model (RRTMG) are used to calculate the RF_p and RF_c of each individual aerosol (SIOA, POA and BC) associated with E_p and E_c of each region. The GEOS-Chem simulated spatial (horizontal and vertical) distributions of individual aerosol species, among other variables, are used as input of RRTMG calculations. Readers are referred to Supplementary Information of Lin et al. (2016) for detailed descriptions of all these steps.

2.2. Defining the five driving factors

The aerosol RF contributed by each region's production or consumption can be decomposed into five factors.

Direct Radiative Forcing at Top-of-the-Atmosphere (unit: 10^{-3} W/m^2)

= Population
∗ Output/Population (Per Capita Output).
(unit: \$/yr)
∗ Emission/Output (Per Output Emission, a.k.a emission intensity).
(unit: g/\$)
∗ Aerosol Mass/Emission (Chemical Efficiency).
(unit: day)
∗ Radiative Forcing/Aerosol Mass (Radiative Efficiency).
(unit: W/m^2/Tg)

$$*\text{Coefficient}\left(=\frac{1}{365 \times 10^9}\right) \tag{1}$$

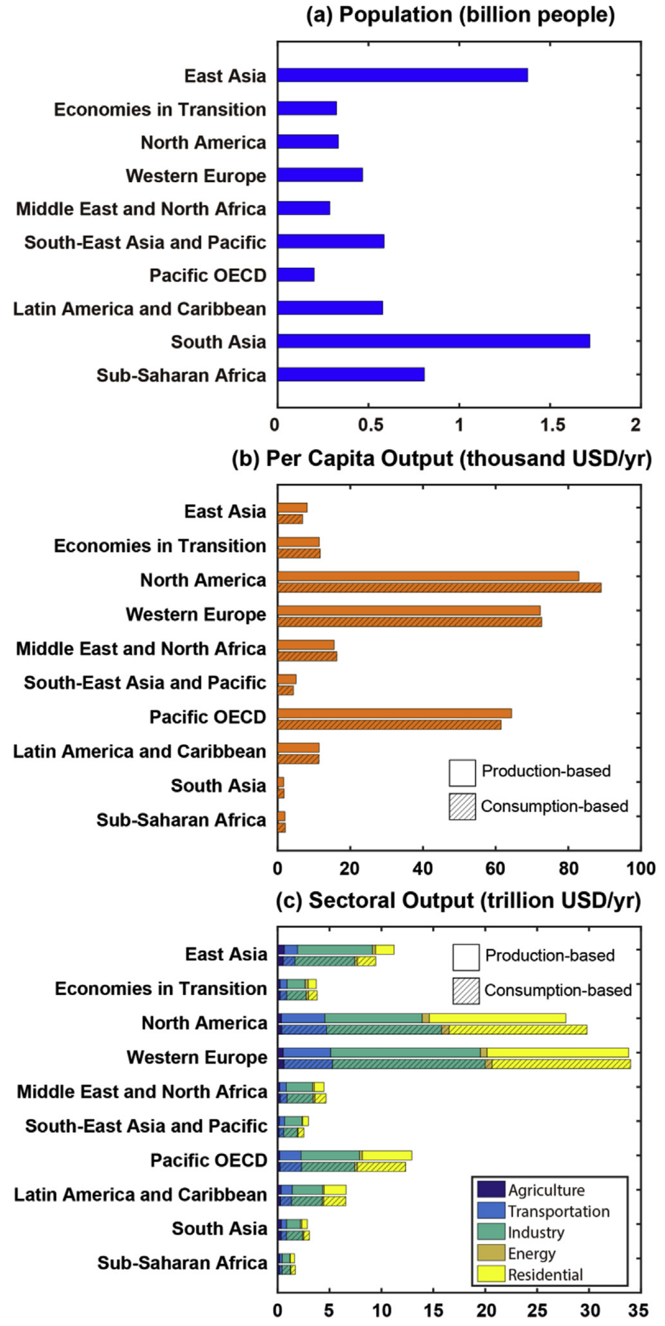

Fig. 3. (a) Population size, (b) per capita output, and (c) sectoral output for each of the 10 regions. For per capita output and sectoral output, the full bar refers to the production-based results and dashed bar refer to the consumption-based results.

Here, “Coefficient” is used for unit conversion. Population, per capita output and emission intensity are three socioeconomic factors, which together determine the amount of emissions associated with a region's production or consumption. The size of population greatly affects the amount of certain production like agriculture and most manufacturing products a region can supply and the amount of consumption that region requires. The population data is from United Nations (UN, https://esa.un.org/unpd/wpp/Download/Standard/Population/). Per capita (monetary) output in a year ($/yr) indicates the economic status of a region. The yearly output data are from GTAP8 (Narayanan et al., 2012). Per output emission (g/$), a.k.a emission intensity, is a critical index summarizing the industrial structure, energy structure, energy efficiency, and end-of-pipe control in a region. Emission intensity is estimated from E_p, E_c and economic output.

Chemical efficiency (day) and radiative efficiency ($W/m^2/Tg$) are two atmospheric factors that depend on the chemical, transport, or radiative states of the atmosphere. Chemical efficiency describes how long a pollutant can remain in the atmosphere, after a given amount of its (or its precursors’) emissions are released. Due to chemical reactions and deposition, the fraction of emitted pollution remaining in the atmosphere declines rapidly and, without continuous emissions, would virtually become zero after a few weeks (for the species studied here). Chemical efficiency is calculated as GEOS-Chem simulated atmospheric pollution mass in 2007 divided by emissions used to drive the CTM, i.e., the emissions analyzed here. Chemical efficiency is the same as the residence time for primary POA and BC aerosols. For SIOA, the chemical efficiency depends on both the speed of conversion from precursor gases (SO_2, NO_X and NH_3) to SIOA and the residence time of SIOA. Here it is calculated as the total SIOA mass divided by the sum of SO_2 (expressed in terms of sulfate, SO_4), NO_X (in terms of nitrate, NO_3) and NH_3 (in terms of ammonium, NH_4) emissions.

Radiative efficiency represents the effectiveness of aerosols in scattering or absorbing sunlight. For a given atmospheric mass of pollutant, its radiative forcing depends on the pollutant's vertical profile and the meteorological environment (clouds, surface reflection, etc.) of the region the pollutant is located in. For a particular region, its E_p of a pollutant differs from E_c in both magnitude and spatial distribution. The difference in spatial distribution means that even if the magnitude of E_p is the same as E_c, the resulting atmospheric spatial distributions of that pollutant are different, and thus the radiative efficiency differs. Radiative efficiency is calculated as the RRTMG simulated global radiative forcing divided by GEOS-Chem simulated atmospheric mass.

The difference between RF_c and RF_p can then be calculated as follows:

$$(RF_c\text{-}RF_p)/RF_p = (E_c{*}FE_c\text{-}E_p{*}FE_p)/(E_p{*}FE_p) = (1+\delta E)*(1+\delta FE)\text{-}1 \quad (2)$$

$$E_c = (1+\delta E)*E_p \quad (3)$$

$$FE_c = (1+\delta FE)*FE_p \quad (4)$$

Here, RF_p and RF_c are the production-based and consumption-based RF, respectively. E_p and E_c are the production-based and consumption-based emissions, respectively; they are the product of population, per capita output and per output emission. FE_p and FE_c are the production-based and consumption-based RF per unit of emissions, respectively; they are the product of chemical efficiency and radiative efficiency. δE and δFE are the relative change from production-based to consumption-based emissions and FE, respectively.

Supplementary Section 1 provides detailed evaluation of RF, aerosol optical depth and vertical profiles simulated here (shown in Fig. S1 and S2), which suggests that our aerosol simulation is reasonable for subsequent analysis of RF drivers.

Although the Structural Decomposition Analysis (SDA) can be used to further analyze the role of production/consumption structure in emission changes over time (Guan et al., 2014b), our study is not focused on the contribution of economic structural change. Thus, for simplicity we have elected not to use SDA for socioeconomic analysis in this study.

3. Production-based RF, consumption-based RF, and their driving factors

3.1. Production- versus consumption-based aerosol direct radiative forcing

We first extend from Lin et al. (2016) to analyze RF_p and RF_c exerted by a region upon its territory and other regions. This acts as a basis for the subsequent analysis of the five driving factors.

Fig. 1 shows RF_p and RF_c exerted by each source region upon each receptor region for SIOA + POA (scattering) and BC (absorbing). Here,

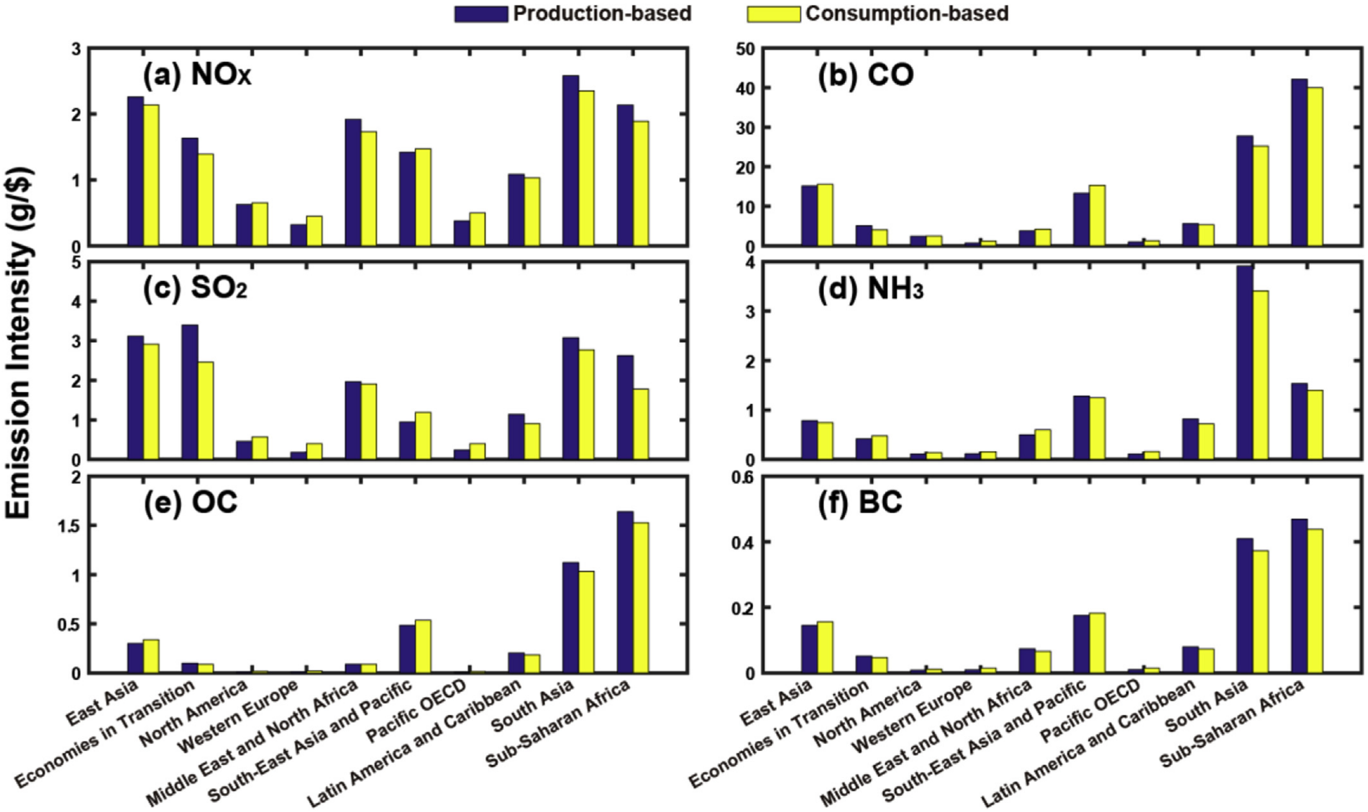

Fig. 4. Production-based (blue bar) and consumption-based (yellow bar) emission intensity of (a) NO_X, (b) CO, (c) SO_2, (d) NH_3, (e) OC and (f) BC for each of the 10 regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

"Rest of World" is combined with all oceanic areas for simplicity. The percentage values inside any table of the figure show how much percent of the forcing exerted by a source region is distributed across the individual receptor regions. The values outside any table denote the total RF, enlarged by 1000 times, by a source region (vertical) or upon a receptor region (horizontal). The percentage values in parentheses for RF_c show the relative change from RF_p to RF_c.

Fig. 1 shows that the global annual mean RF_p exerted by a source region ranges from −0.012 to −0.174 W/m^2 for SIOA + POA and from 0.004 to 0.085 W/m^2 for BC. The range for RF_c is notably smaller, at (−0.018)–(-0.142) W/m^2 for SIOA + POA and 0.007–0.077 W/m^2 for BC. This means that the variation of forcing associated with regional consumption is smaller across regions than the forcing associated with regional production. East Asia, South Asia and Sub-Saharan Africa together contribute over half of the global forcing for both RF_p and RF_c. The magnitude of RF_p is larger than RF_c in East Asia and South Asia, whereas the opposite is true for Western Europe, North America and Pacific OECD. The forcing exerted by a source region upon other receptor regions is larger than the forcing upon itself, as a result of atmospheric transport (affecting both RF_p and RF_c) and trade-embedded emission relocation (relevant to RF_c).

The percentage values inside the tables of Fig. 1 show that a large portion of RF_p (32–74% for SIOA + POA and 19–63% BC) and RF_c (35–64% for SIOA + POA and 20–58% for BC) exerted by any source region is upon the remote "Rest of World" and oceanic areas. This highlights the contribution of regionally produced aerosols to climate forcing at a global scale. In addition, the share of RF_c exerted by a source region upon its own territory is always smaller than the share for RF_p (see the diagonal values of the tables), because some of its consumption-related emissions are physically released in foreign regions. For North America SIOA + POA, such self-forcing share reduces from 46.9% for RF_p to 29.0% for RF_c. The respective change for Western Europe is from 30.0% to 14.3%, with the latter number (14.3%) equal to the RF_c exerted by Western Europe upon Economies in Transition. For BC, the RF_c exerted by Western Europe upon Economies in Transition (16.2%) even surpasses that upon Western Europe itself (12.1%). This is in part because 11% of the economic import of Western Europe is supplied by Economies in Transition (Fig. 2(b)), and that Economies in Transition is downwind from Western Europe. Also, consumption by Pacific OECD leads to more RF_c upon East Asia than upon itself (12.5% versus 7.6% for SIOA + POA and 12.6% versus 9% for BC), mainly due to its large import from East Asia (Fig. 2(b)).

3.2. Socioeconomic factors affecting regions' RF_p and RF_c

Fig. 3(a) compares the population size across 10 source regions. "Rest of World" has few people and emissions and is thus not discussed. Population size is a critical factor determining the capability of a region to provide affordable labor for economic production and to provide consumption demand. That many developing countries have become the manufacturing bases of industrial products is largely because of their enormous population, which means relatively inexpensive labor supply and a large market. Fig. 3(a) shows that across the 10 regions, the size of population varies by a factor of nine, with Pacific OECD having the fewest population (0.2 billion) and South Asia (1.7 billion) and East Asia (1.3 billion) being the top two populated regions. China is the main country in East Asia and the most populous country in the world, but its population growth rate has declined from 0.68%/yr in 2000 to 0.43%/yr in 2017 (www.Worldometers.info). India is the main country in South Asia, and it still maintains a high population growth rate (1.13%/yr in 2017). It is expected that Indian population will surpass China by 2020, which also means enormous changes in economic production and consumption. By comparison, although North America contains five times as much land as South Asia, its population size is just 20% of the latter.

Fig. 3(b) presents production-based and consumption-based per

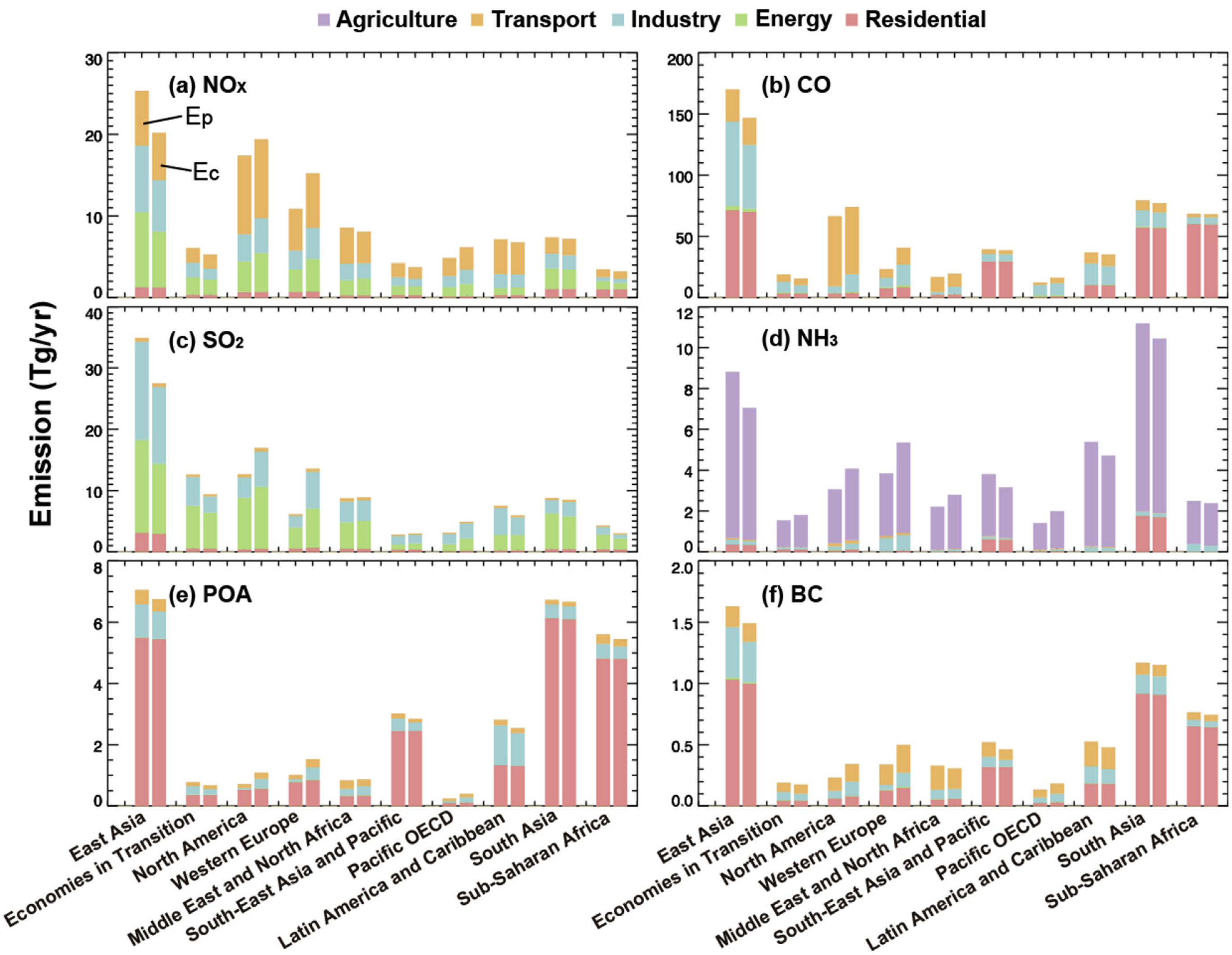

Fig. 5. Annual E_p (left bar) and E_c (right bar) of (a) NOx, (b) CO, (c) SO_2, (d) NH_3, (e) POA and (f) BC for five sectors in 10 regions in 2007.

capita output in 2007 in each region. Per capita output reflects the economic development level of a region, with a higher value usually representing higher productivity, affluence and living conditions. Across the regions, production-based and consumption-based per capita output varies by a factor of about 40, with the developed regions having much higher values than the developing regions. North America has the highest production-based and consumption-based per capita output, despite its modest population size (Fig. 3(a)) and low population density. As a result, North America has enormous output (28 and 30 Trillion US Dollar for production-based and consumption-based outputs, respectively), second only to Western Europe (33 and 34 Trillion US Dollar) (Fig. 3(c)). By comparison, South Asia, Sub-Saharan Africa, South-East Asia and Pacific, and East Asia have the lowest per capita output. The lowest per capita output also means lowest total output for South Asia and Sub-Saharan Africa (Fig. 3(c)).

Fig. 4 presents emission intensity (per output emission) for six pollutant species for both E_p and E_c of each region. Here production-based emission intensity refers to the ratio of E_p to production-related output, and the consumption-based emission intensity refers to the ratio of E_c to consumption-related output. For both E_p and E_c, emission intensity is generally high for all species in East Asia and South Asia, which greatly contribute to their high emissions. Emission intensity is also high over Sub-Saharan Africa, which together with its lowest output among the 10 regions (Fig. 3(c)) means modest-to-high emissions, including being the third highest E_p and E_c among the regions for both POA and BC (Fig. 5). Sub-Saharan Africa has lower consumption-based than production-based emission intensity, thus its E_c is lower than E_p (Fig. 5) despite its consumption-based output being higher than its production-based output (Fig. 3(c)). A similar case exists for South Asia, whereas an opposite case occurs for Pacific OECD.

Fig. 4 shows that North America, Western Europe and Pacific OECD have rather low production-based emission intensity, which more than offsets their high per capita output and results in low emissions (Fig. 5). However, their emission intensity for E_c is much more than the intensity for E_p. Thus their E_c is larger than E_p by a factor of 1.6 for Western Europe SIOA, 1.7 for Pacific OECD POA, and 1.5 for North America BC. Secondly, although the production-based industrial and residential (including household and commercial) outputs in North America, Western Europe and Pacific OECD are much higher than in most developing regions (Fig. 3(c)), the opposite result is true for respective E_p (Fig. 5). This contrast is attributed to cleaner industry, cleaner energy source, and more stringent emission control in these developed regions, as well as their large amount of outsourced polluting industrial production (Lin et al., 2014; Peters et al., 2011).

3.3. *Atmospheric factors affecting regions' RF_p*

Fig. 6(a)-(c) shows chemical efficiency (CE_p) with respect to E_p of each region for SIOA, POA and BC. The aerosol mass due to a region's E_p is simulated with GEOS-Chem, by including or excluding such E_p. As the

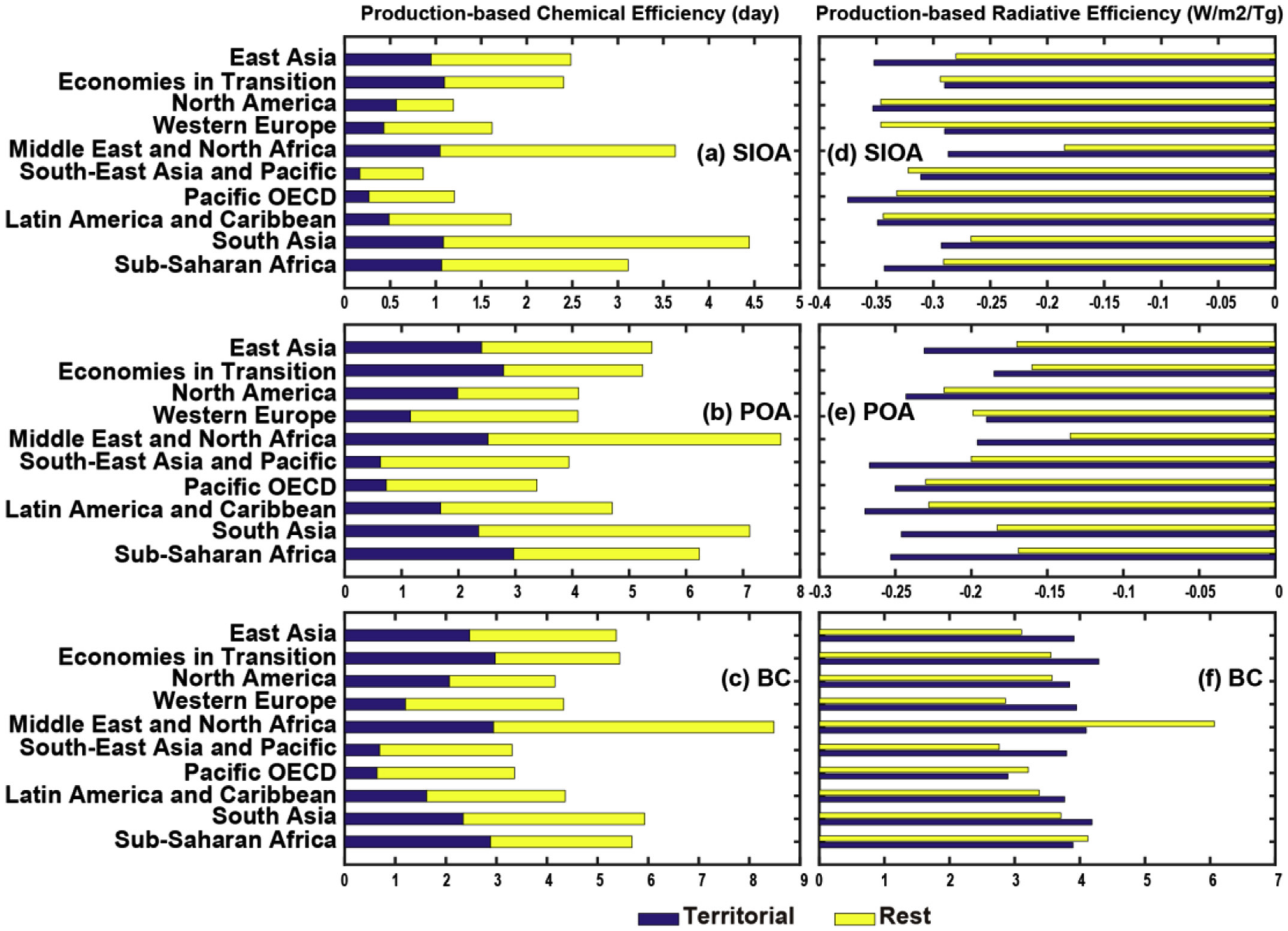

Fig. 6. Production-based chemical efficiency and radiative efficiency of SIOA, POA and BC for the territorial (blue bar) and the rest (yellow bar) regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

aerosol mass consists of a portion over the source region (blue bars for "territorial" in Fig. 6(a)-(c)) and the other portion outside the region (yellow bars for "rest"), CE_p is decomposed to respective two parts.

For SIOA (Fig. 6(a)), CE_p changes by a factor of five across the 10 source regions. CE_p is the smallest for South-East Asia and Pacific (0.8 days) due to strong wet scavenging of this highly solvable aerosol over such a rainy tropical region. CE_p is also small (1.2–1.6 days) over North America, Western Europe, Pacific OECD, and Latin America and Caribbean. This means that the low aerosol loading over the developed regions benefits significantly from their low CE_p. CE_p is modest (2.4–3.1 days) over East Asia, Economics in Transition, and Sub-Saharan Africa. It reaches 3.6–4.5 days over Middle East and North Africa (dry area) and South Asia. Although South Asia receives heavy rains from the summer monsoon, it has much less frequent precipitation in other times for wet scavenging of aerosols. Also, the large convective flux (Stjern et al., 2016) carries South Asian aerosols to high altitudes with extended lifetime and horizontal transport. The resulting effect is evident: the "rest" portion of CE_p for South Asia is highest among the 10 regions, about twice of East Asia and Western Europe and five times of North America.

Across the 10 regions, CE_p arranges from 3.4 to 7.6 days for POA (Fig. 6(b)) and from 3.3 to 8.5 days for BC (Fig. 6(c)). These values are much higher, with the cross-regional spread much smaller, than CE_p for SIOA, because most of POA and BC are hydrophobic and cannot be wet deposited. Middle East and North Africa has the highest chemical efficiency for both POA (7.6 days) and BC (8.5 days). Therefore, although E_p of POA for Middle East and North Africa is lower than South-East Asia and Pacific (Fig. 5), its global annual mean RF_p is 2–3 times stronger. South Asia has the second highest CE_p for POA (7.2 days) and BC (5.9 days). By comparison, Pacific OECD and South-East Asia and Pacific have the lowest CE_p for both POA (3.4–4.0 days) and BC (3.3–3.4 days). For these two regions, the "territorial" share of aerosol mass is very small, reflecting that most pollutants are emitted at their coastal areas and can be easily transported out of their territories. The "territorial" share is also small for Western Europe, reflecting that most pollutants originating from this region that remain in the atmosphere are located above Economics in Transition and other downwind regions.

Fig. 6(d)-(f) shows the radiative efficiency (RE_p) with respect to each region's E_p for SIOA, POA and BC. Here RE_p is calculated separately for aerosols over the territory of a region (blue bar) and for aerosols outside its territory (yellow bar). Overall, RE_p of BC (2.6–6.0 W/m^2/Tg) is about 10 times as much as those for SIOA and POA. The cross-regional spread of RE_p is within a factor of two, much smaller than the spread in CE_p. Also, the cross-regional spread of RE_p for aerosols outside the source region (yellow bar) is within 30%, much smaller than the spread for aerosols over the territory (blue bar). Thus, although how long aerosols can stay in the atmosphere depends greatly on where emissions are released, the global annual mean RF exerted by aerosols remained in the atmosphere is much less sensitive to the region of emission.

Fig. 6(d)-(f) shows that the territorial portion of RE_p (blue bar) by

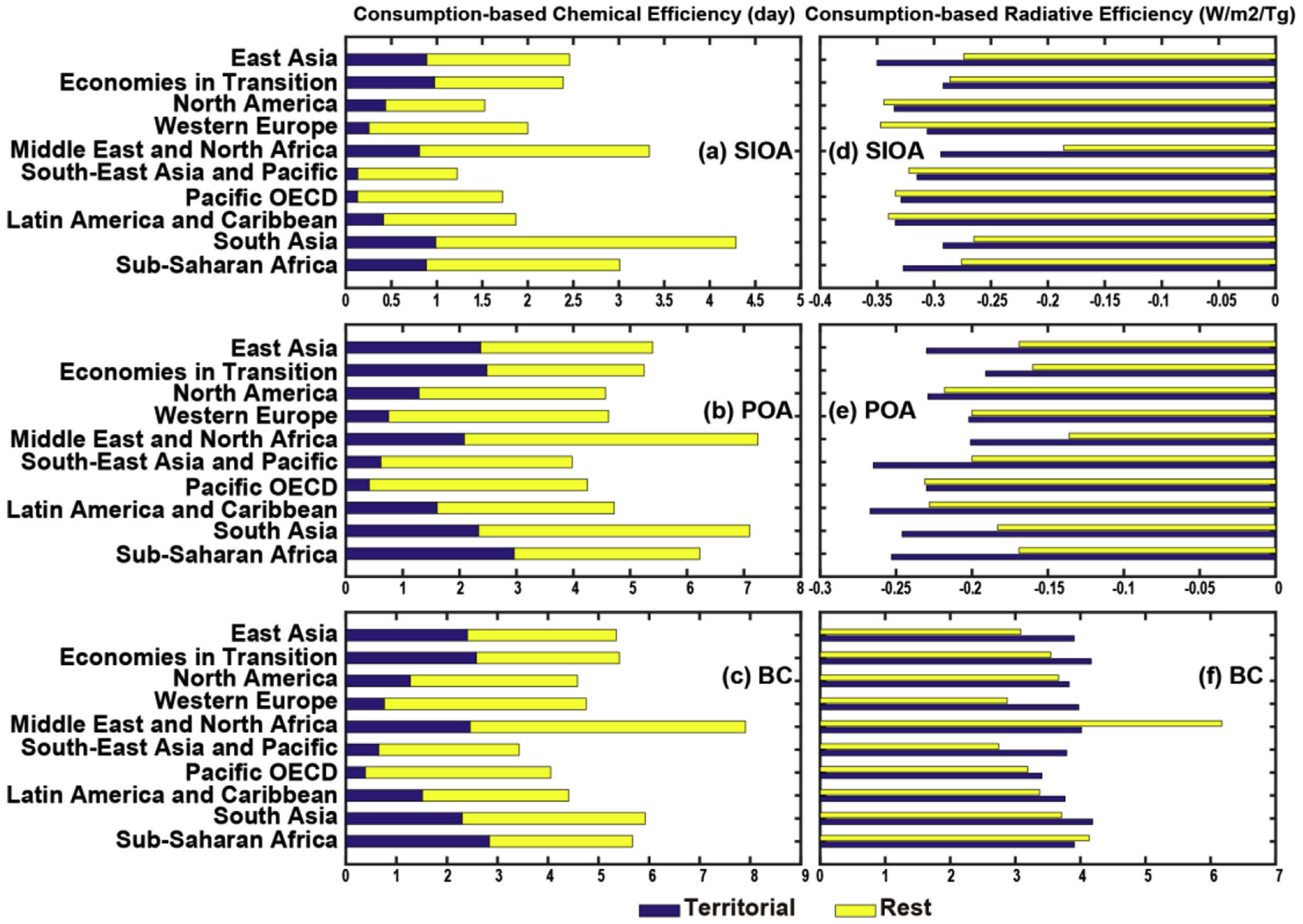

Fig. 7. Consumption-based chemical efficiency and radiative efficiency of SIOA, POA and BC for the territorial (blue bar) and the rest (yellow bar) regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Middle East and North Africa is the weakest for SIOA and POA but the strongest for BC among the 10 regions. This is because of strong surface reflectance over this desert-dominated land greatly that reduces the forcing by scattering aerosols and enhances the absorption by BC. Thus, although Middle East and North Africa has relatively low BC E_p (6th among the 10 regions), its high chemical efficiency and high radiative efficiency strengthen its BC RF_p (4th among the 10 regions).

Our results are comparable to previous studies for a few common regions (supplementary, section 2).

3.4. Atmospheric factors affecting regions' RF_c

Fig. 7(a)-(f) shows the consumption-based chemical efficiency (CE_c) and radiative efficiency (RE_c). Here the CE_c is the mass of aerosols induced by unit consumption-based emissions, and the RE_c is the radiative forcing induced by unit mass of aerosols related with consumption-based emissions. For SIOA, the CE_c is the total mass of sulfate, nitrate and ammonia divided by the total consumption-based emission of SO_2 (expressed as sulfate), NO_X (expressed as nitrate) and NH_3 (expressed as ammonium). For any region as a consumer, its CE_c is essentially a weighted average of CE_p across the 10 regions, with weights being the portion of that region's E_c physically released in respective producing regions. Although CE_c is generally close to CE_p for most regions, there are notable exceptions. For South-East Asia and Pacific, CE_c is higher than CE_p by 50% for SIOA, because this region has the lowest CE_p among the 10 regions (Fig. 6(a)), and 31% of its consumption is imported from regions with high CE_p (Fig. 2(b)). For similar reasons, CE_c is higher than CE_p by 40% for Pacific OECD for SIOA, POA and BC. By comparison, Middle East and North Africa has the highest CE_p for POA and BC (Fig. 6(b)-(c)), thus its CE_c is smaller than CE_p by 6% and 8% respectively.

RE_c is very close to RE_p for almost any region (Fig. 7(d)-(f) versus Fig. 6(d)-(f)). RE_c is essentially a weighted average of RE_p. Because of the small cross-regional difference in RE_p (Fig. 6(d)-(f)), the averaging does not lead to a significant change from RE_p to RE_c.

4. Drivers of the difference between RF_c and RF_p

Fig. 8 summarizes the relative change in each region's RF, emissions (product of population, per capita output and emission intensity as socioeconomic factors) and per emission forcing (product of chemical efficiency and radiative efficiency as atmospheric factors, FE in Eq. (2)) from being an economic exporter to being an importer. See Eqs. 2–4 for the relationship between these factors and how their changes are calculated. For SIOA, Western Europe has the largest change from RF_p to RF_c (107%), which is mainly due to the difference between E_p to E_c (63%), although the change in per emission forcing also plays a role (26%). The RF changes are also large for Pacific OECD (83%) and North America (50%), with comparable contributions from the change in emissions and the change in per emission forcing. As the largest economic exporter (Fig. 2(a)), East Asia has lower RF_c than RF_p by 20% predominantly due to its lower E_p than E_c, which is in turn driven by its much higher E_p intensity than its main economic importers (Pacific OECD, Western Europe and North America). For South-East Asia and

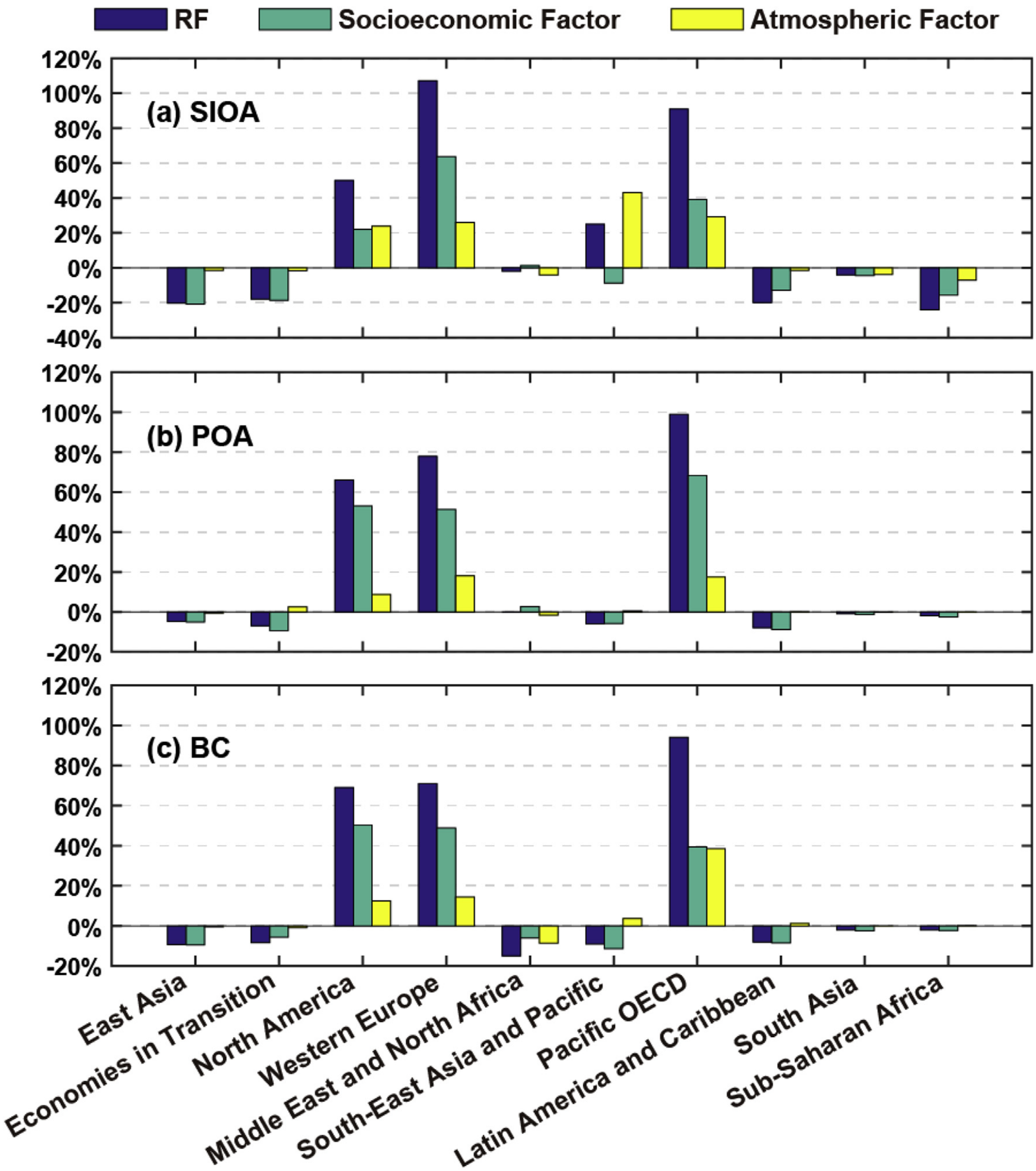

Fig. 8. Percentage change from production-to consumption-based results for RF (blue bar), emissions (product of all socioeconomic factors, green bar), per emission forcing (product of all atmospheric factors, yellow bar). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Pacific, although its E_c is lower than E_p by 9%, its per emission RF_c exceeds RF_p by 43%, which leads to higher RF_c than RF_p by 30%. For Middle East and North Africa, the increase from E_p to E_c is overcompensated by the reduction in per emission forcing, which results in an overall reduction from RF_p to RF_c.

For POA of each region (Fig. 8(b)), the change from E_p to E_c is the dominant factor determining the sign and magnitude of change from RF_p to RF_c. Nevertheless, the change in per emission forcing is also important for most regions. For example, the changes in RF for Pacific OECD (100%), Western Europe (80%) and North America (67%) are partly due to the changes in per emission forcing (by 19%, 19%, 9%, respectively). For Economics in Transition, the increase in per emission forcing partly compensates for the reduction in emissions.

For BC (Fig. 8(c)), the significant enhancement from RF_p to RF_c by Pacific OECD (by 94%) is roughly equally contributed by the increase in per emission forcing and the increase in emissions. For the decrease from RF_p to RF_c for Middle East and North America, the decrease in per emission forcing is a more important factor than the decrease in emissions. For other regions, the change in emissions is more important than the change in per emission forcing in driving the change from RF_p to RF_c.

Overall, our results suggest that socioeconomic factors are often the main driver of the change in RF of a region from being an economic producer to a consumer. However, depending on the region and pollutant species, the importance of atmospheric factors may be comparable or even greater than socioeconomic factors.

5. Concluding remarks

This study reveals the complex roles of socioeconomic (population, per capita output, and emission intensity) and atmospheric factors (CE and RE) in determining a region's aerosol radiative forcing from both production and consumption perspectives. Each socioeconomic factor varies by 1–2 orders of magnitude across the 10 source regions; whereas the cross-regional variability in each atmospheric factor (CE and particularly RE) is below a factor of five. These factors can act together or offset each other in determining a source region's RF ranking among all source regions.

Although socioeconomic factors (that together determine emissions) are often more important than atmospheric factors (that together determine per emission forcing) in causing the difference between RF_p and RF_c, there are notable exceptions. For example, the RF difference for SIOA and BC of Pacific OECD (by 83% and 94%, respectively) is roughly equally contributed by the change in emissions and that in per emission forcing. For SIOA of South-East Asia and Pacific and Middle East and North America, the change from RF_p to RF_c is determined by the change in per emission forcing partly compensated by the change of opposite sign in emissions. For BC of Middle East and North America, the decrease from RF_p to RF_c is determined by the decrease in per emission forcing facilitated by the decrease in emissions.

Our delineation of RF-related socioeconomic and atmospheric factors contributes to regional attribution of climate change and improvement of mitigation strategies. Under the economic globalization, the production and associated emissions in a region may be connected to consumption worldwide. The impact of such emissions on radiative forcing is also global through further atmospheric processes. Thus, pollution physically released from any region has its global relevance from the point of view of both emission attribution and radiative forcing impacts. This study provides evidence for policymaking the merit of actions against pollution induced climate change as a globally collective effort. Furthermore, the quantified driving factors in this study can be used for subsequent analysis of regions' mitigation pathways. For example, the values of emission intensity, chemical efficiency, and radiative efficiency for each region can be coupled with the output of socioeconomic models to quantify the radiative impacts of certain mitigation actions by that region.

Clearly, the complexity from both socioeconomic and atmospheric processes is also applicable to other aerosol-induced environmental problems such as public health threat, crop damage and ecological deterioration. As controlling aerosols are important for many reasons, international discussion to cooperative regional pollution mitigation must take into account these socioeconomic and atmospheric factors (Guan et al., 2014a). The quantitative values of various factors here can be used to facilitate this discussion and further policy considerations aiming to achieve environmentally sustainable socioeconomic development.

Author declaration

We wish to confirm that there are no known conflicts of interest associated with this publication.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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Appendix A. Supplementary data

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