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Long-term trends of direct nitrous oxide emission from fuel combustion in South Asia

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Abstract

An increasing concentration of nitrous oxide (N_2O) in the global atmosphere can perturb the ecological balance, affecting the climate and human life. South Asia, one of the world's most populous regions, is a hotspot for N_2O emission. Although agriculture traditionally dominated the region, economic activities are rapidly shifting towards industry and energy services. These activites may become the largest emitters of N_2O in future. Yet, few attempts have been made to estimate long-term direct N_2O emission from fuel combustion for the different energy-consuming sectors in the South Asian region. Therefore, the present study developed a comprehensive sectoral N_2O emission inventory for South Asian countries for the time period of 1990–2017, with projections till 2041. It revealed that the average N_2O emission from fuel combustion in the South Asia region is about 40.96 Gg yr^{-1} with a possible uncertainty of ±12 Gg yr^{-1}, showing an increase of more than 100% from 1990 to 2017. Although India is the major contributor, with an average of 34 Gg yr^{-1} of N_2O emissions, in terms of growth, small countries like Bhutan and Maldives are dominating other South Asian countries. Sector-wise, the residential sector contributed a maximum emission of 14.52 Gg yr^{-1} of N_2O but this is projected to reduce by more than 50% by 2041. This is because of the successful promotion of cleaner fuels like liquefied petroleum gas over more polluting fuelwood. Power generation contributed 9.43 Gg yr^{-1} of N_2O emissions, exhibiting a maximum growth of 395%, followed by road transport (289%) and industry (231%). Future N_2O emissions from transport, power and industry are projected to rise by 2.8, 3.3, and 23.9 times

their 2017 estimates, respectively, due to the incapability of current policies to combat rising fossil fuel consumption. Mitigation options, such as replacing diesel and compressed natural gas vehicles with electricity-driven vehicles, can decelerate N_2O emissions to 45% by 2041 for road transport. A 41% reduction is possible by displacing coal with renewables in the power and industry sectors. Overall, the South Asian contribution to global N_2O emissions has enlarged from 2.7% in 1990 to 5.7% in 2007–2016, meaning there is an urgent need for N_2O emission mitigation in the region.

1. Introduction

Nitrous oxide (N_2O), an important module of air pollution and climate change, plays a crucial role in regulating the greenhouse balance on earth as it is 273 times more potent as a greenhouse gas (GHG) than carbon dioxide (IPCC-AR6 2021). It is the main driver of stratospheric ozone depletion, leading to a high risk of cancer. Its concentration has increased globally by more than 20%, from 270 to 331 ppb during the period 1750–2018 (Myhre *et al* 2013, Tian *et al* 2020). This rising atmospheric burden of N_2O can perturb the earth's radiation budget, producing radiative forcing that affects climate-air, water and soil systems.

South Asia, with ~1.86 billion people sharing only 4.9% of the global landmass (SAARC 2018), has emerged as one of the global hotspots of N_2O emission and nitrogen (N) pollution (Tian *et al* 2020, Raghuram *et al* 2021). The ever-increasing food and energy demands of an expanding population are driving anthropogenic N_2O emissions from agriculture, waste generation, and fossil fuel burning in power, transport, industry, residential and other sectors in the region.

Fortunately, the scientists and governments of South Asian countries (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka) are recognizing and responding to the growing nitrogen challenge. The pioneering scientific efforts of the Indian Nitrogen Group since 2006, which established the South Asian Nitrogen Centre of International Nitrogen Initiative (INI) and hosted the 5th International Nitrogen Conference in Delhi in 2010, catalysed action within and beyond the region (Abrol *et al* 2008, Galloway *et al* 2008, SACEP 2014). The South Asia Co-operative Environment Programme (SACEP), the South Asian Seas Programme, the Global Environment Facility-United Nations Environment Pragramme-INI project 'Towards the Establishment of an International Nitrogen Management System' and the UK Research and Innovation - Global Challenges Research Fund South Asian Nitrogen Hub further widened the regional and international engagement for sustainable N management (Sutton *et al* 2013, Raghuram *et al* 2020).

The Indian Nitrogen Assessment (Abrol *et al* 2017) and South Asian cooperation facilitated the India-led United Nations (UN) resolution on 'sustainable nitrogen management' in UNEP (2019). Most recently, Pakistan also conducted its N assessment (Aziz *et al* 2021), making South Asia the only region to publish two national N assessments. The regional implementation of the UN resolution requires updated and comprehensive emission inventories of all species of reactive nitrogen (Nr), such as N_2O, NO_X and NH_3. They are important for depicting past, present and future trends from different sectors in all South Asian countries for informed interventions, which are currently unavailable.

Nitrogen inventory studies conducted so far have mostly concentrated on agriculture and food production sectors, and N_2O from fossil fuel combustion received relatively lesser attention both globally and regionally (Dangal *et al* 2019, Kurokawa and Ohara 2020, Ladha *et al* 2020, Galloway *et al* 2021). Presently, agriculture dominates the South Asian N_2O emission concerns (Shahzad *et al* 2019, Pathak *et al* 2021) but its growing economies are rapidly enhancing N_2O emissions from waste, energy, industry and transport (Bhattacharya *et al* 2017).

However, comprehensive N_2O inventories targeting these sectors at the local, regional and global levels for the policy makers are lacking. Very few studies estimate the long-term N_2O emissions from fossil fuels in South Asia, despite the growing recognition of its global importance (van Aardenne *et al* 2001, Ohara *et al* 2007, Tian *et al* 2020). The most recent study related to Nr quantification, by Galloway *et al* (2021), also lacked a detailed account of N_2O emission from fuel combustion in South Asian region.

Consequently, the present study aims to develop an updated and comprehensive N_2O emission inventory for South Asia focusing on (a) countrywide and year-by-year N_2O emission estimation from fossil fuel combustion in the South Asian region from energy sectors (power, transport, industry and others) for the period of 1990–2017; (b) the assessment of historical, current and future emissions to understand the regional realities of implemented policies and (c) new policy options to reduce N_2O emission in the region.

2. Methods

2.1. General methodology

Depending upon the quality and sources of activity data, N_2O emission from fuel combustion has been estimated by deploying tier I methodology

(IPCC 2006). N_2O calculations were done for power generation, industry (manufacturing and construction industries), transport (roads, railways, aviation and navigation of ships/vessels), residential, commercial, agriculture and other energy sectors for all eight South Asian countries, based on the equation given below:

$$\text{Emissions (Gg)} = \sum_{i=1}^{n} (\text{Ac} * \text{EF})\, i$$

where Ac = activity data (fuel consumption in TJ); EF = emission factor (kg TJ^{-1}); i = economic sectors (1, 2, 3…n).

2.2. Activity data: fuel consumption

Activity data (Ac) refers to the magnitude of human activity resulting in emissions during the given period of time, such as data on energy use, fuel consumption, land areas, lime and fertiliser use, waste generation etc (TNC, Nepal 2017). In the present study, N_2O emission rates have been estimated as a function of fuel consumption. Fuel consumption data for India were mainly assembled from country-based resources, including the Ministry of Statistics and Programme Implementation, the Ministry of Petroleum and Natural Gas (MoPNG), and a system for the estimation of greenhouse gases emissions the GHG Platform of India. In some sectors like transport and residential sectors, UN data values were also used to fill the gaps. Data related to vehicular population, railway passengers, air passengers and navigation traffic were obtained from the road transport year book of India (2015–2017); the Indian railways statistical yearbook (2017 and 2018); Directorate General of Civil Aviation, India, and Indian Shipping Stats (2018). For Pakistan, fuel consumption and other datasets have been procured from the International Energy Agency (IEA), UN data and Pakistan Bureau of Statistics. Fuel consumption for Bhutan was extracted from the petroleum, oil and lubricants import data managed by the Department of Trade, Ministry of Economic affairs, Royal Government of Bhutan. Vehicular population and air passenger data for Bhutan were obtained from statistical year books of Bhutan from 1996 to 2018 (National Statistics Bureau, Bhutan). In the case of Nepal, fuel consumption datasets were collected from the IEA, UN data, and Nepal Oil Corporation, whereas data relevant to traffic volume in road transport and aviation were downloaded from the Central Bureau of Statistics, Nepal and the Department of Transport Management, Nepal. With the paucity of fuel consumption data for Afghanistan, Maldives, Bangladesh and Sri Lanka from national sources, UN and IEA datasets have been used. Other datasets for these countries related to traffic volume in railways, aviation, navigation and on roads were collected from different national sources like the National Statistics and Information Authority of Islamic Republic of Afghanistan, the

Bangladesh Road Transport Authority, Bangladesh Bureau of Statistics, National Bureau of Statistics Maldives, Statistics Department-Central Bank of Sri Lanka (supplementary information table 1 available online at stacks.iop.org/ERL/17/045028/mmedia).

2.3. Emission factors (EFs) and tier selection

An EF represents the ratio of the amount of N_2O generated to the amount of fuel consumed and is expressed as kilograms of N_2O emitted per teragram of fuel burned. Based on EF availability, the Intergovernmental Panel on Climate Change (IPCC) has recommended three approaches for N_2O estimation including (a) tier I that employs default IPCC EF with coarse activity data like national or global data, (b) tier II that employs EF and activity data defined by the country and (c) tier III that uses higher order methods, including models and inventory measurement systems tailored to address national circumstances, repeated over time and driven by disaggregated levels (IPCC 2006).

The EFs are generally controlled by fuel type, combustion facility/technology and respective emission control levels adopted across the different economic sectors in any country. To cover the variability of EFs in different source categories due to differences in combustion technologies applied, sector/source-based IPCC EFs have been applied for different economic sectors. Further, to cover changes in EFs with respect to changes in combustion technology and respective emission control levels with time, revised IPCC (2006) N_2O EFs were deployed to estimate the emissions instead of IPCC (1996) EFs (table 1).

However, there is a substantial paucity of country-specific combustion-technology-based EF and fuel consumption data in the public domain for each fuel in each sector for different South Asian countries. This made it difficult to adopt IPCC tier II and tier III methodology to develop the present inventory. So, the IPCC tier I approach was adopted for all the South Asian countries.

2.4. Scenarios for future projections

Under the business-as-usual scenario (BAS), future fuel consumption and emission projections in South Asia were performed based on the annual growth rates (GRs) averaged over the last seven years (2010–2017) for dominant fuels used in different economic sectors (figure 1 and table 2). Subsequent future fuel consumption and emissions were estimated considering 2017 values as reference.

Five mitigation scenarios with low emission rates due to strong and relevant policy change, were developed to mitigate N_2O emission from power generation, transport, industry and residential sectors (figure 1 and table 2).

In the transport sector, mitigation scenarios were developed in line with rising diesel consumption in the road subsector. In most South Asian countries,

Table 1. Sector-based IPCC-prescribed EFs used to estimate N_2O emission in different South Asian countries.

Sector	Fuel type	N_2O EF (kg TJ^{-1})	Sector	Fuel type	N_2O EF (kg TJ^{-1})	Sector	Fuel type	N_2O EF (kg TJ^{-1})	Sector	Fuel type	N_2O EF (kg TJ^{-1})
Road	Diesel (HSDO)[h]	3.9	Railways	Diesel (HSDO)[h]	28.6	Navigation	Diesel (HSDO)[h]	3.9	Aviation	Jet kerosene/ATF[g]	2.0
	MG (petrol)[a]	3.2		Fuel/furnace oil	0.6		LDO[c]	0.6			
	NG including LNG[b]	3.0		LDO[c]	0.6		Fuel/furnace oil	2.0			
	LDO[c]	0.6		LPG[e]	0.2		MG (petrol)[a]	3.2			
	Furnace oil	0.6		Coal	1.5						
	LSHS[d]	0.6									
	LPG[e]	0.2									
	CNG[f]	3.0									
Industry	Coal/hard coal	1.5	Power	Diesel (HSDO)[h]	0.6	Residential	Kerosene	0.6	Commercial	NG including LNG[b]	0.1
	Diesel (HSDO)[h]	0.6		Coal/hard coal	1.5		Charcoal	1.0		LPG[e]	0.1
	MG (petrol)[a]	0.6		Fuel/furnace oil	0.6		Fuel/firewood	4.0		Kerosene	0.6
	Naptha	0.6		NG including LNG[b]	0.1		Diesel (HSDO)[h]	0.6		Fuel wood/wood	4.0
	Kerosene	0.6		LDO[c]	0.6		LPG[e]	0.1		Diesel (HSDO)[h]	0.6
	Fuel/furnace oil	0.6		LSHS[d]	0.6		Natural gas	0.1		Fuel/furnace oil	0.6
	Natural gas	0.1		LPG[e]	0.1		Coal/cooking coal	1.5			
	LPG[e]	0.1		Naptha	0.6		Coke	1.5			
	Lubricants	0.6									

(Continued.)

Table 1. (Continued.)

Sector	Fuel type	N$_2$O EF (kg TJ^{-1})	Sector	Fuel type	N$_2$O EF (kg TJ^{-1})	Sector	Fuel type	N$_2$O EF (kg TJ^{-1})	Sector	Fuel type	N$_2$O EF (kg TJ^{-1})
	Fuel/firewood	4.0	Agriculture	Diesel (HSDO)[h]	0.6	Others	MG (petrol)	0.6			
	LDO[c]	0.6		NG including LNG[b]	0.1		Other oil products	0.6			
	LSHS[d]	0.6		LDO[c]	0.6		NG including LNG[b]	0.1			
	Other oil products	0.6		Fuel/furnace oil	0.6		Diesel (HSDO)[h]	0.6			
	Lignite	1.5		LSHS[d]	0.6		LDO[c]	0.6			
	Oven coke	1.5		LPG[e]	0.1		Furnace oil	0.6			
	Timber	4.0		Kerosene	0.6		LSHS[d]	0.6			
							LPG[e]	0.1			
							Kerosene	0.6			

Source: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, vol 2: Energy, ch 2 and ch3.

Note.

[a] MG (petrol) = motor gasoline (petrol).

[b] NG including LNG = natural gas including liquefied natural gas.

[c] LDO = light diesel oil.

[d] LSHS = low sulphur heavy stock.

[e] LPG = liquefied petroleum gas.

[f] CNG = compressed natural gas.

[g] ATF = aviation turbine fuel.
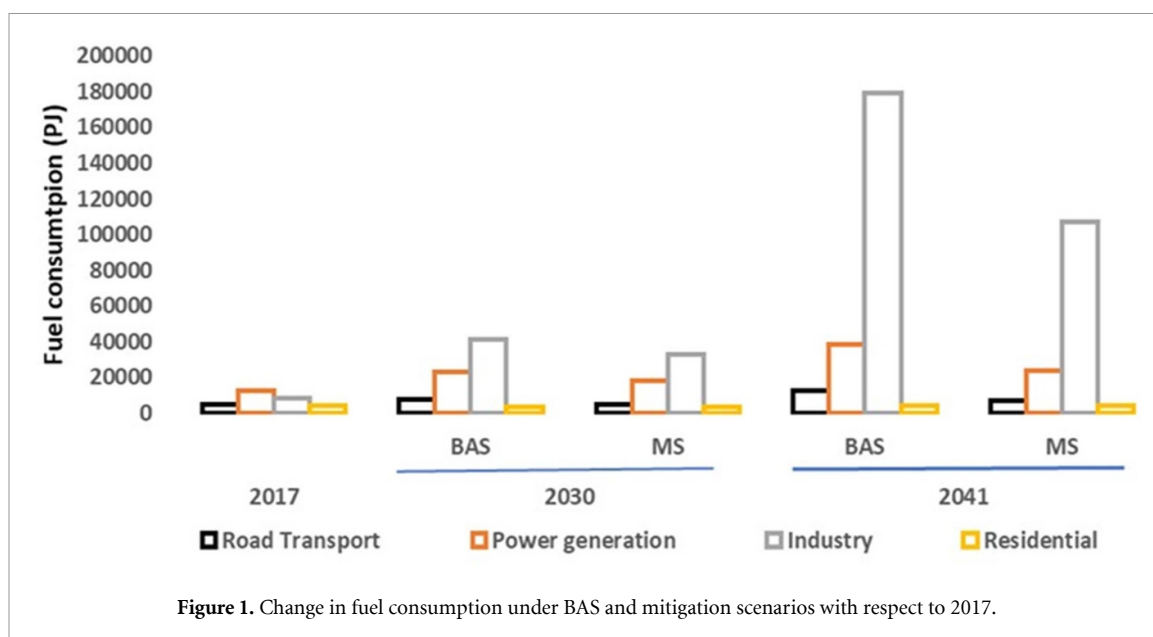
[h] HSDO = high speed diesel oil.

Figure 1. Change in fuel consumption under BAS and mitigation scenarios with respect to 2017.

Table 2. Description of mitigation scenarios for South Asia.

Economic sector	Dominant fuel used	Annual GR considered under BAS	Mitigation scenario
Road transport	Diesel	5.1%	Switching 51% diesel consumption to CNG (intervention 1).[a] Switching 51% diesel and 50% CNG consumption to electricity (intervention 2).[b]
Industry	Coal	14.5%	Displacing the 22% coal with renewables[b]
Power	Coal	5.2%	Displacing the 22% coal with renewables[c]
Residential	Fuelwood	−5.9%	Displacing the 20% LPG with solar powered induction stoves.[b]

[a] PPAC (2013).
[b] Author assumption.
[c] Thambi *et al* (2018); CNG = compressed natural gas; LPG = liquefied petroleum gas.

except Bhutan, diesel is the dominant transport fuel for buses, heavy and light commercial vehicles like trucks, taxis, metro-cabs and other utility vehicles, leading to accelerated N_2O emission in the region. Further, mitigation scenarios for power generation and industry were developed following nationally determined contribution (NDC) scenarios defined by South Asian countries to meet the targets of the Paris Climate Accord. Under NDC scenarios, South Asian countries, particularly India, have promoted the use of renewable energy (solar, hydro, wind energy) to displace coal for mid- to long-term electricity generation in the power sector to combat rising air pollution (Thambi *et al* 2018). A similar assumption (displacing coal with renewables) was also applied to industry for future projections. In the residential sector, fuelwood is the dominant fuel used. However, its consumption has declined over time due to the promotion of liquefied petroleum gas (LPG) for domestic purposes, leading to a fall in N_2O emissions under BAS. A mitigation scenario promoting the use of solar-powered induction stoves in the residential sector was

also proposed to keep N_2O emission under control in the long run (Bhattacharya *et al* 2017).

2.5. Statistical analysis
Results were statistically analysed using SPSS-16.0 Statistical Software for Windows. Uncertainties in the results were checked for the coefficient of variation (CV). The higher the CV, the greater the level of dispersion of values around the mean, leading to high uncertainty in the results. Pearson correlation matrix analysis was also conducted to validate the results with National Communication (NATCOM) estimates submitted to the United Nations Framework Convention on Climate Change by each South Asian country partner.

3. Results and discussion

3.1. Patterns of fuel consumption
The net fuel consumption in South Asia has more than tripled from 10 244 PJ in 1990 to 30 834 PJ in 2017, a growth of 201%, reflecting enhanced energy

Figure 2. Sector-wise and country-wise fuel consumption trends of South Asia from 1990 to 2017.
Note: In figure (a.1), the left (primary) side of the *y*-axis represents the fuel consumption data (PJ) for electricity generation, industry (manufacturing and construction), and road sector, while the right (secondary) side of the *y*-axis depicts the fuel consumption data (PJ) for aviation, navigation, and railways. In figure (a.2), the primary *y*-axis represents the fuel consumption data (PJ) for agriculture, commercial and other activities, while the secondary *y*-axis shows the fuel consumption data (PJ) for residential activities from 1990 to 2017 for the entire South Asian region. In figure (b), each ring represents fuel consumption (PJ) in each year during 1990–2017 for all sectors. In figure (c), each ring stands for fuel consumption (PJ) averaged over a five year time period for all the South Asian countries, leading to a reduction in the number of rings to seven due to averaging.

demand to support rapid urbanization and economic development. Electricity generation emerged as the dominant fuel consumer in the region with a mean consumption of 7013 PJ per annum during 1990–2017 (figure 2(b)). A variety of fuels such as coal, natural gas and fuel oil were used for power generation. However, coal-based power generation dominated the entirety of South Asia and its share had increased from 83% to 89% with time (figure 3(a)). India showed the largest mean annual fossil fuel consumption for power generation (6194 PJ) in the region, followed by Pakistan (524 PJ) and Bangladesh (250 PJ) during the period 1990–2017.

Total fuel consumption in the industrial sector tripled from 2491 PJ (1990) to 8257 PJ (2017) showing a growth of 231% (figure 2(a.1)). Coal was the dominant industrial fuel and its share has increased from 76% to 83% (figure 3(b)). Other fuels including lignite, oven coke, diesel, fuelwood, timber, gasoline, naphtha, kerosene, fuel oil, natural gas, LPG, lubricants, low sulphur heavy stock (LSHS) and other oil products were also consumed in industry. At the country level, the mean annual fuel consumption in the industrial sector followed the trend of India (3344 PJ) > Pakistan (546 PJ) > Bangladesh (105 PJ).

In the transport sector, total fuel consumption increased from 1448 PJ (1990) to 5056 PJ (2017) with a growth of 249% due to positive growth in all modes of transport (figure 4). Road transport exhibited a maximum mean fuel consumption of 2097 PJ per

annum during the period 1990–2017. This is evident from the rise in the number of motor vehicles with time at a compounded annual growth rate (CAGR) of 9.7% (figures 4(a) and (b)). Diesel and gasoline were the most prominent fuels consumed in the road sector (figure 3(d)).

For the aviation sector, total fuel consumption increased from 104 PJ in 1990 to 327 PJ in 2017, averaging to 185 PJ per annum, due to a continuous upsurge in the number of air passengers carried with a CAGR of 9.7% (figures 4(c) and (d)). Jet kerosene/aviation turbine fuel (ATF) was the predominant fuel used in aircrafts (figure 3(g)). However, diesel was also utilised for ground operations and support services at airports (Abrol *et al* 2017).

Mean fuel consumption on the railways of South Asia declined to 90 PJ in 2000–2009 then 154 PJ during 1990–1999, leading to a fall in its share of the transport sector. This is because the share of coal consumption in railways reduced from 57% in the 1990s to almost zero by 2000 (figure 3(e)). However, fuel consumption increased again in 2010 and onwards due to enhanced diesel consumption from 40% (1990) to 99% (2017) driven by an increase in railway traffic at a CAGR of 5.2% (figures 3(e) and (4e)).

Owing to the rise in the number of vessels or ships, fuel consumption also increased in marine navigation with a mean fuel consumption of 44 PJ per annum (figures 2 and 4(f)), led by India (31 PJ) > Bangladesh
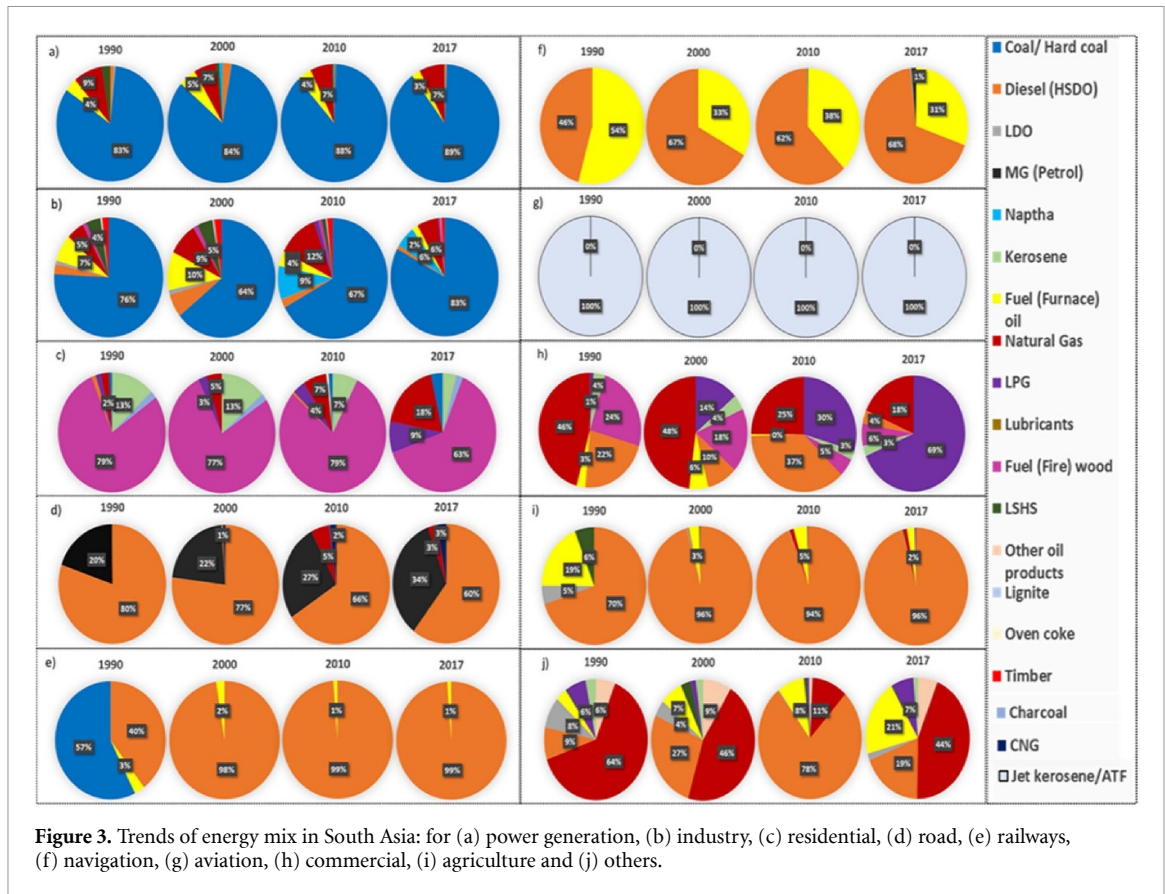
Figure 3. Trends of energy mix in South Asia: for (a) power generation, (b) industry, (c) residential, (d) road, (e) railways, (f) navigation, (g) aviation, (h) commercial, (i) agriculture and (j) others.

(11 PJ) > Maldives (2.1 PJ) > Sri Lanka (0.33 PJ). The dominant fuel used in the navigation subsector included diesel and fuel oil (figure 3(f)). The huge consumption of Maldives relative to the size of the country and its population is explained by the fact that marine navigation is the only mode of transport that connects the country's large number of islands and tourist sites. However, taking all sectors of transport as a whole, India's sheer size in area, as well as population and transport needs, define its predominant mean annual fuel consumption of 1823 PJ, followed by Pakistan (418 PJ), Sri Lanka (77 PJ) and Bangladesh (74 PJ) over the period of 28 years.

In the residential sector, total fuel consumption increased by 34% from 3381 PJ in 1990 to 4322 PJ in 2017. The mean fuel consumption was calculated as 4533 PJ per annum. In fact, total residential consumption declined in 2014 and onwards, due to the promotion and preference of LPG over traditional fuelwood or cow dung cakes for cooking in rural South Asia (figure 2(a.2)). Although fuelwood was the dominant fuel used in the residential sector, kerosene, charcoal, diesel, LPG, natural gas, coke and cooking coal were also consumed for cooking, lightening and space heating (figure 3(c)). India showed the maximum mean annual fuel consumption of 3389 PJ followed by Pakistan, Bangladesh and Nepal, with mean annual fuel consumptions of 428, 315 and 270 PJ, respectively, for the residential sector in the region.

Mean annual energy consumption for commercial and agriculture sectors were estimated as 106 and 176 PJ, respectively, from 1990 to 2017. Energy in the commercial sector was mainly consumed for lighting, refrigeration, ventilation, cooking, computers and office equipment, space and water heating and other similar activities at commercial places. In agriculture, diesel was used to run tractors, harvesters, combines harvesters, water pumps and generators.
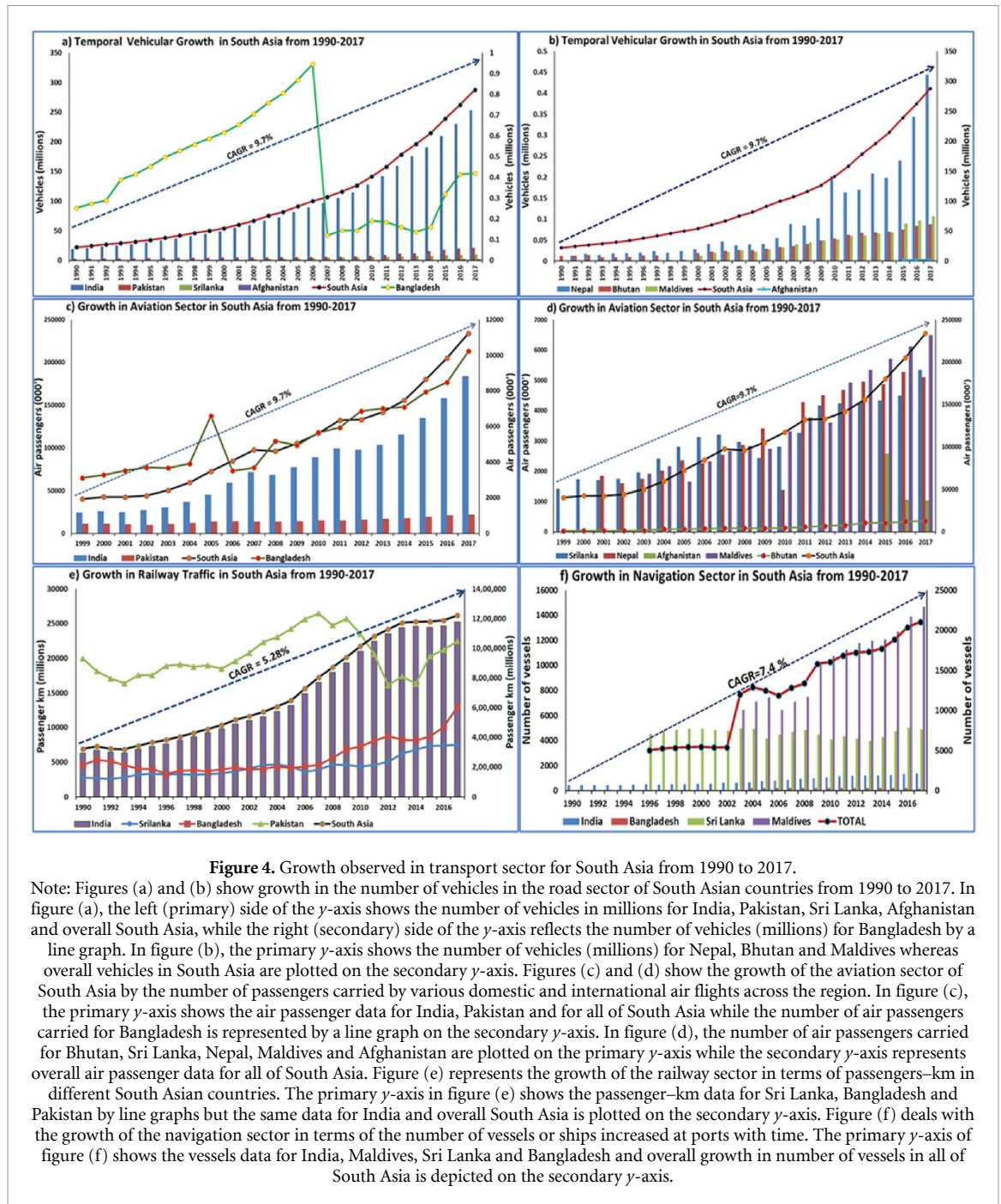
Energy consumption for nonenergy, nonspecified and other miscellaneous activities have been covered under the category of 'others'. Mean energy consumption under this category was 615 PJ per annum during 1990–2017.

The overall pattern of mean fuel energy consumption per annum in South Asia over the period of 28 years was led by India (15 331 PJ), followed by Pakistan (2105 PJ), Bangladesh (845 PJ) and Nepal (309 PJ; figure 2(c)). Further, on a sectoral basis, overall fuel consumption in the region followed the trend of power generation > residential > industry > road transport > others > aviation > agriculture > commercial > navigation (figure 2(b)).

3.2. Trends in N_2O emission
3.2.1. National estimates
Total N_2O emissions in South Asia from fuel combustion varied from 24.95 to 61.31 Gg yr^{-1} in the study period, exhibiting a net gain of 146% over time, indicating a direct relationship between fuel consumption

Figure 4. Growth observed in transport sector for South Asia from 1990 to 2017.
Note: Figures (a) and (b) show growth in the number of vehicles in the road sector of South Asian countries from 1990 to 2017. In figure (a), the left (primary) side of the *y*-axis shows the number of vehicles in millions for India, Pakistan, Sri Lanka, Afghanistan and overall South Asia, while the right (secondary) side of the *y*-axis reflects the number of vehicles (millions) for Bangladesh by a line graph. In figure (b), the primary *y*-axis shows the number of vehicles (millions) for Nepal, Bhutan and Maldives whereas overall vehicles in South Asia are plotted on the secondary *y*-axis. Figures (c) and (d) show the growth of the aviation sector of South Asia by the number of passengers carried by various domestic and international air flights across the region. In figure (c), the primary *y*-axis shows the air passenger data for India, Pakistan and for all of South Asia while the number of air passengers carried for Bangladesh is represented by a line graph on the secondary *y*-axis. In figure (d), the number of air passengers carried for Bhutan, Sri Lanka, Nepal, Maldives and Afghanistan are plotted on the primary *y*-axis while the secondary *y*-axis represents overall air passenger data for all of South Asia. Figure (e) represents the growth of the railway sector in terms of passengers–km in different South Asian countries. The primary *y*-axis in figure (e) shows the passenger–km data for Sri Lanka, Bangladesh and Pakistan by line graphs but the same data for India and overall South Asia is plotted on the secondary *y*-axis. Figure (f) deals with the growth of the navigation sector in terms of the number of vessels or ships increased at ports with time. The primary *y*-axis of figure (f) shows the vessels data for India, Maldives, Sri Lanka and Bangladesh and overall growth in number of vessels in all of South Asia is depicted on the secondary *y*-axis.

and N_2O emission at the country level. The N_2O emission at the country level followed the order of India > Pakistan > Bangladesh > Nepal (table 3). In accordance with the country size, population and fuel consumption, India topped the region and emitted about 34 Gg yr^{-1} of N_2O emission. However, in terms of growth, smaller countries like Bhutan have shown the highest temporal per cent rise in N_2O emission, followed by Maldives. This is because Bhutan is one of the fastest growing economies in the world with a gross domestic product (GDP) of 7.5% in 2017 (SAARC 2018), registering a CAGR of 10% in fuel consumption. This can be attributed to a rising energy demand from industrial, transport and building sectors. Fuel consumption in Maldives also

grew rapidly with a CAGR of 8%, driven by a strong energy demand from transportation and infrastructure sectors, booming tourism and growth in per capita income.

In contrast, fuel consumption in India has grown steadily at a CAGR of 4% from 1990 to 2017, about half that of Bhutan and Maldives with the concomitant smaller percentage rise in temporal N_2O emission (table 3). This might have been aided by the various policy interventions developed by the Indian government, like the National Urban Transport Policy, 2014 (MoUD 2014), the Graded Response Action Plan of Delhi, 2017 (MoEFCC 2017) and the National Clean Air Programme, 2019 (MoEFCC 2019) to control air pollution at national and state level.

Table 3. Country-wise change in N_2O emission (Gg yr^{-1}) in South Asia from 1990 to 2017.

Year	Afghanistan	Bangladesh	Bhutan	India	Maldives	Nepal	Pakistan	Sri Lanka	Total South Asia
1990	0.098	1.156	0.001	20.445	0.007	0.464	2.202	0.573	24.945
1991	0.093	1.173	0.001	21.242	0.007	0.587	2.220	0.582	25.904
1992	0.053	1.211	0.001	22.199	0.010	0.656	2.367	0.618	27.115
1993	0.053	1.215	0.001	22.980	0.008	0.771	2.503	0.610	28.142
1994	0.054	1.210	0.001	23.960	0.008	0.842	2.579	0.632	29.286
1995	0.054	1.282	0.001	24.995	0.010	0.948	2.624	0.649	30.564
1996	0.053	1.295	0.002	26.280	0.011	0.966	2.761	0.703	32.071
1997	0.053	1.337	0.002	26.241	0.014	0.980	2.826	0.683	32.135
1998	0.052	1.341	0.002	26.680	0.012	1.008	2.942	0.693	32.730
1999	0.045	1.322	0.002	26.066	0.017	1.041	2.977	0.716	32.185
2000	0.047	1.321	0.002	26.633	0.016	1.065	3.082	0.738	32.904
2001	0.050	1.410	0.002	26.876	0.017	1.087	3.093	0.747	33.281
2002	0.050	1.417	0.002	25.229	0.022	1.118	3.125	0.742	31.704
2003	0.062	1.422	0.002	25.774	0.002	1.144	3.223	0.762	32.391
2004	0.061	1.478	0.006	26.580	0.003	1.168	3.435	0.779	33.509
2005	0.075	1.492	0.010	31.650	0.002	1.197	3.414	0.762	38.602
2006	0.091	1.522	0.007	35.213	0.026	1.213	3.560	0.754	42.387
2007	0.100	1.522	0.008	40.759	0.027	1.241	3.945	0.756	48.358
2008	0.182	1.562	0.008	43.484	0.022	1.306	3.852	0.770	51.186
2009	0.240	1.584	0.008	43.594	0.021	1.350	3.916	0.839	51.552
2010	0.348	1.653	0.008	42.735	0.011	1.374	3.931	0.877	50.936
2011	0.458	1.825	0.011	42.968	0.011	1.147	3.998	0.890	51.308
2012	0.407	1.849	0.012	46.076	0.012	1.315	3.976	0.888	54.535
2013	0.308	1.802	0.012	48.901	0.024	1.482	4.033	0.891	57.454
2014	0.267	1.861	0.014	50.128	0.041	1.676	4.286	0.951	59.223
2015	0.303	1.978	0.014	52.372	0.041	1.561	4.612	0.987	61.867
2016	0.241	1.969	0.016	49.339	0.048	1.661	4.961	1.074	59.309
2017	0.225	2.095	0.016	50.515	0.050	1.741	5.606	1.059	61.306
Mean (μ)	**0.147**	**1.511**	**0.006**	**33.925**	**0.018**	**1.147**	**3.430**	**0.776**	**40.960**
Std. (σ)	**0.125**	**0.271**	**0.005**	**10.878**	**0.013**	**0.319**	**0.841**	**0.135**	**12.453**
Increase (%)	**128**	**81**	**1828**	**147**	**637**	**276**	**155**	**85**	**146**
Uncertainty (%)	**85**	**18**	**87**	**32**	**74**	**28**	**25**	**17**	**30**

Note: Uncertainties for individual countries, as well as for the whole of South Asia, have been estimated in terms of coefficient of variation (CV) and CV% = $(\sigma/\mu) \times 100$ for each dataset.

3.2.2. Sectoral evaluations

The sectoral profile of N_2O emission in South Asia revealed that despite less fuel consumption than power generation, the residential sector was the major N_2O contributor (table 4, figures 5 and 6). This is because fuelwood, the dominant fuel consumed in the residential sector, is less energy efficient with a low heat content (15.6 TJ Gg^{-1}) and a high N_2O EF (4 kg TJ^{-1}; IPCC 2006). However, in terms of growth over time, power generation represented the major growing sector with a 395% rise in N_2O emission. This is caused by the augmented use of coal in power generation driven by a rise in the per capita energy consumption from 246 to 705 kWh during 1990–2017 (https://data.worldbank.org). Therefore, rising coal consumption has created an ever-rising burden of fossil fuel for power generation in South Asian countries, except for Bhutan and Nepal, where most of the electricity demand is met through hydropower (TNC, Nepal 2017, TNC, Bhutan 2020).

Conversely, the temporal N_2O emission profile from the residential sector (figures 5 and 6) indicated a stabilised growth with only a 4% rise during the period 1990–2017. This might be due to a drop in fuelwood consumption from 79% (1990) to 63% (2017) triggered by an enhanced share of cleaner and more energy-efficient fuels like LPG and natural gas from 2010 onwards in domestic activities (figure 3(c)). Therefore, in addition to fuel consumption, N_2O emission in South Asia across different sectors are also controlled by the variety/types of fuels and their respective heat content and EFs revised over time. Further, the industrial sector contributed about 5.32 Gg yr^{-1} of N_2O emission, showing a positive growth of 231% from 1990 to 2017 (table 4; figures 5 and 6). Increases in industrial N_2O emission is chiefly caused by the increased coal consumption in manufacturing and construction industries like mining, chemical and petrochemical, fertiliser, pulp and paper, textile and leather, iron and steel, pharmaceuticals, food processing and tobacco and others.

In the transport sector, N_2O emission varied as road > railways > aviation > navigation depending upon the fuel consumption, fuel efficiency and incorporation of revised EFs. The road sector contributed the highest amount of N_2O among all modes of transport, covering around 68.2% of emission from transport. As a whole, the road sector emerged as the thirrd largest N_2O contributor after residential and power generation, and the second fastest growing sector after power generation in N_2O emission in the region (table 4; figures 5 and 6).

Railways covered 27.2% of N_2O emission generated from transport, higher than aviation (3.3%) and navigation (1.3%). But, in line with fuel consumption, the railway has shown retarded growth in N_2O emission over time because of the gradual replacement of coal with diesel (a more energy-efficient fuel than coal with a heating value of 43 TJ Gg^{-1}

greater than coal (25.8 TJ Gg^{-1})) in conjunction with electricity promotion, modernization and technical upgrades (Gurjar *et al* 2017). Thus, the resultant energy savings with reduced coal consumption in railways, particularly in India and Pakistan, have led to a better performance, attaining only a 66% rise in N_2O emission in South Asia.

Aviation and navigation covered 3.3% and 1.3% of N_2O emission in the transport sector, showing a rise in emission by 216% and 134%, respectively, from 1990 to 2017. Positive growth in the aviation sector can be attributed to the rising ATF fuel consumption, whereas positive growth in navigation is driven by uplifting diesel consumption with time.

Commercial, agriculture and other miscellaneous nonspecified activities contributed about 0.44 Gg yr^{-1} of N_2O emission collectively because of enhanced fuel consumption in hotels, schools, hospitals, offices, shopping malls, places of worship and increased mechanization and irrigation by ground water via pumps in agriculture. To summarise, N_2O emission across different sectors in South Asia varied as residential > power generation > road transport > industry > railways > aviation > others > navigation > agriculture > commercial. Thus, the residential sector emerged as a major N_2O contributor whereas the commercial sector was the smallest N_2O contributor in the region. As a whole, fossil fuel combustion in all these anthropogenic activities collectively emitted 40.96 Gg yr^{-1} (0.041 Tg yr^{-1}) of N_2O from 1990 to 2017. Moreover, the South Asian contribution to global N_2O emissions from fossil fuel combustion has enlarged from 2.7% in 1990 (0.025 Tg yr^{-1} of global 0.90 Tg yr^{-1}) to 5.7% in 2007–2016 (0.054 Tg yr^{-1} of 0.95 Tg yr^{-1}; Tian *et al* 2020) suggesting that thereis a serious need for interventions in the region.

3.2.3. Uncertainty analysis

Our study has effectively captured the national, sectoral and temporal variability of N_2O emission in the South Asian region with an overall uncertainty of 30%. The current results are satisfactory, with an uncertainty of ± 12 Gg yr^{-1} in the net N_2O emission of 40.96 Gg yr^{-1}. Our results are further validated by a strong positive correlation ($r = 0.977$ at $p = 0.01$) between the present study N_2O estimates and NATCOM values. The present inventory is more significant and original than the NATCOM national inventories as it provides long-term N_2O estimates for each South Asian country for 28 years. NATCOM provides N_2O estimates for each South Asian country once in a five year period and NATCOM data is highly scattered in space as well because few countries have reported substantially. Thus, the present study facilitates much better temporal and spatial N_2O comparisons for well-informed policy interventions towards N_2O pollution reduction and sustainable Nr management in the South Asian region.

Table 4. Sector-wise change in N_2O emission ($Gg\ yr^{-1}$) in South Asia from 1990 to 2017.

Year	E.G.[a]	Industry[b]	Road tran.[c]	Railways	Aviation	Navigation	Residential	Commercial	Agriculture	Others	Total S.A.[d]
1990	3.44	3.41	4.20	2.44	0.21	0.08	11.06	0.03	0.02	0.06	24.945
1991	3.67	3.56	4.33	2.65	0.20	0.09	11.30	0.03	0.02	0.06	25.904
1992	4.06	3.70	4.69	2.75	0.19	0.09	11.50	0.03	0.02	0.06	27.115
1993	4.45	3.70	4.99	2.92	0.19	0.09	11.66	0.04	0.03	0.07	28.142
1994	4.88	3.79	5.30	3.07	0.21	0.11	11.80	0.04	0.03	0.07	29.286
1995	5.21	3.95	5.73	3.17	0.23	0.11	12.00	0.04	0.03	0.09	30.564
1996	5.91	3.80	5.94	3.74	0.24	0.12	12.12	0.04	0.08	0.09	32.071
1997	6.34	3.84	4.97	3.99	0.25	0.18	12.22	0.04	0.20	0.11	32.135
1998	6.58	3.88	5.15	3.96	0.25	0.18	12.37	0.04	0.20	0.13	32.730
1999	6.96	3.67	5.73	2.02	0.27	0.10	13.04	0.05	0.20	0.14	32.185
2000	7.60	3.32	5.98	2.08	0.28	0.10	13.12	0.04	0.22	0.16	32.904
2001	8.07	3.47	5.30	2.31	0.27	0.11	13.34	0.04	0.22	0.15	33.281
2002	8.37	3.51	3.12	2.41	0.27	0.11	13.52	0.04	0.21	0.15	31.704
2003	8.45	3.83	3.27	2.36	0.28	0.10	13.68	0.04	0.21	0.17	32.391
2004	8.93	3.97	3.42	2.41	0.31	0.12	13.86	0.04	0.21	0.22	33.509
2005	9.60	4.13	3.38	2.70	0.35	0.13	17.72	0.08	0.21	0.31	38.602
2006	10.00	4.61	4.72	2.68	0.40	0.17	19.21	0.08	0.21	0.31	42.387
2007	10.56	5.09	8.73	2.91	0.44	0.19	19.63	0.09	0.18	0.55	48.358
2008	11.35	5.63	9.43	2.94	0.47	0.21	19.78	0.09	0.04	1.26	51.186

(Continued.)

Table 4. (Continued.)

Year	E.G.[a]	Industry[b]	Road tran.[c]	Railways	Aviation	Navigation	Residential	Commercial	Agriculture	Others	Total S.A.[d]
2009	11.92	5.93	9.68	3.08	0.47	0.23	18.83	0.09	0.04	1.29	51.552
2010	12.13	5.01	10.63	3.18	0.49	0.22	18.07	0.10	0.04	1.07	50.936
2011	12.56	5.48	11.57	3.38	0.53	0.22	17.23	0.10	0.05	0.20	51.308
2012	13.88	6.89	12.37	3.45	0.56	0.18	16.88	0.10	0.05	0.18	54.535
2013	15.02	8.31	12.87	3.56	0.55	0.16	16.68	0.11	0.05	0.15	57.454
2014	15.30	9.24	13.36	3.73	0.56	0.17	16.59	0.11	0.04	0.13	59.223
2015	15.53	10.87	14.16	3.84	0.59	0.17	16.40	0.11	0.04	0.15	61.867
2016	16.13	11.19	15.41	3.89	0.64	0.18	11.60	0.07	0.05	0.16	59.309
2017	17.03	11.29	16.32	4.04	0.65	0.20	11.48	0.07	0.05	0.16	61.306
Mean (μ)	**9.43**	**5.32**	**7.67**	**3.06**	**0.37**	**0.15**	**14.52**	**0.06**	**0.11**	**0.27**	**40.960**
Std. (σ)	**4.12**	**2.51**	**4.10**	**0.62**	**0.15**	**0.05**	**2.96**	**0.03**	**0.08**	**0.35**	**12.453**
Increase (%)	**395**	**231**	**289**	**66**	**216**	**134**	**4**	**102**	**173**	**188**	**146**
Uncertainty (%)	**44**	**47**	**53**	**20**	**41**	**31**	**20**	**45**	**80**	**127**	**30**

Note: Uncertainties for individual countries, as well as for whole South Asia, have been estimated in terms of coefficient of variation (CV) and CV% = $(\sigma/\mu) \times 100$ for each dataset.

[a] Electricity generation.
[b] Industry include manufacturing and construction industries.
[c] Road transport.
[d] South Asia.
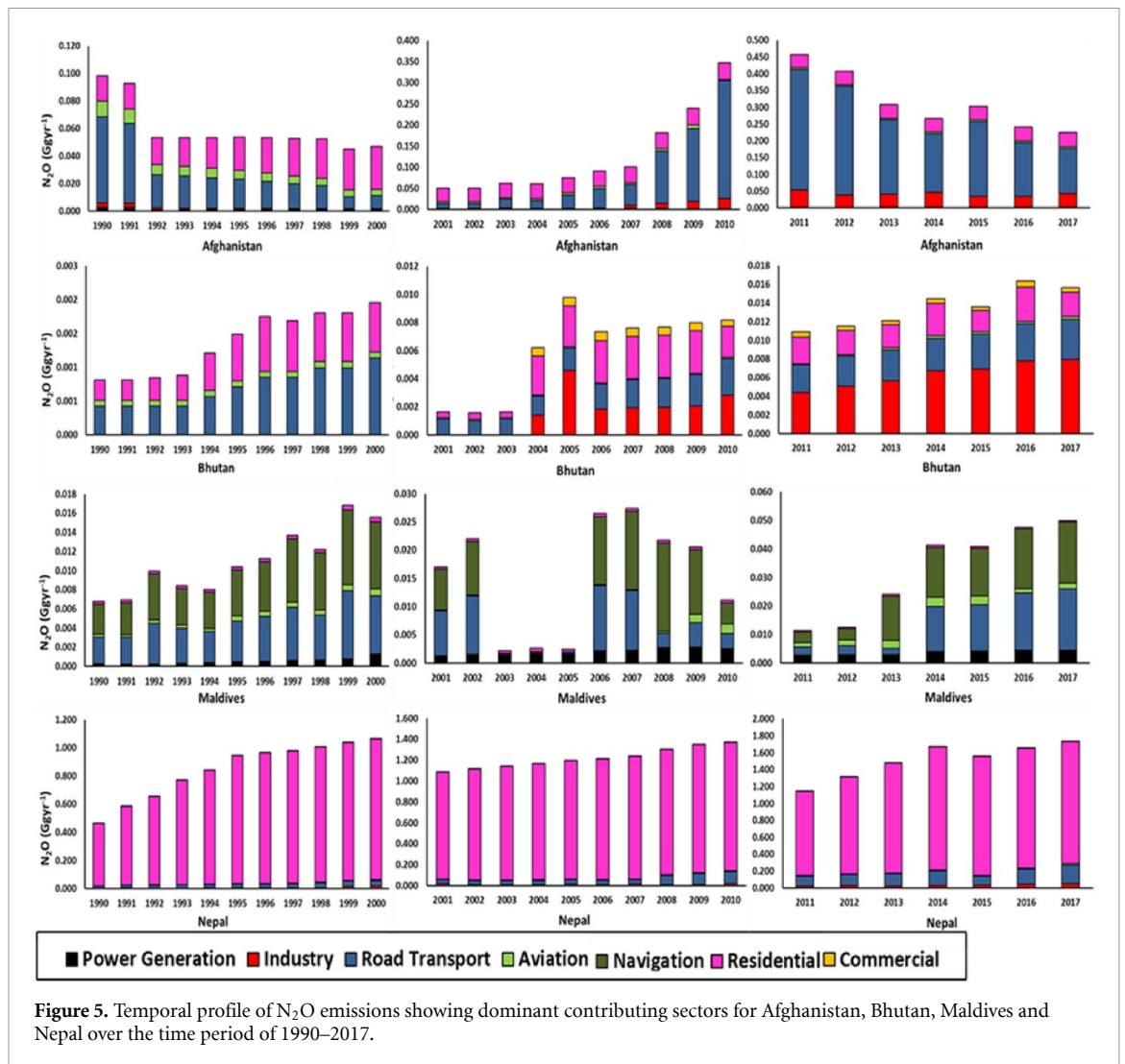
Figure 5. Temporal profile of N$_2$O emissions showing dominant contributing sectors for Afghanistan, Bhutan, Maldives and Nepal over the time period of 1990–2017.

Most of the uncertainty induced in the estimates of the present study is mainly associated with the activity data (fuel consumption) and EFs deployed. Country-wise, Afghanistan, Bhutan and Maldives have shown high uncertainty (table 3). This uncertainty in the estimates is brought by the paucity of long-term reliable and accurate fuel consumption data available in the public domain or the unexpected fall or rise in fuel consumption with time due to changing energy-consuming activities in these countries. For example, in the case of Afghanistan, the maximum uncertainty of 79% noticed in N$_2$O estimates during the period 2001–2010 (supplementary information table 3) may be responsible for increasing the total uncertainty of Afghanistan estimates to 85% due to fluctuating fuel consumption in the industry and road sectors and a sharp rise in fuel consumption during 2010–2011 in both the sectors to support the industrial and economic development (supplementary information figure 1). High uncertainty in Bhutan N$_2$O estimates can be attributed to the maximum uncertainty observed in N$_2$O estimates of the industry sector (127%) and the

commercial sector (104%) from 1990 to 2017 due to the nonavailability of fuel consumption data in the public domain for these sectors prior to 2004 (supplementary information table 6). In the case of Maldives, the high uncertainty of N$_2$O estimates is mainly driven by the augmented uncertainty observed in the transport sector, particularly during 2001–2010. This is because of the very irregular pattern of fuel use observed in the road, aviation and navigation subsectors of transport in Maldives (supplementary information figure 2) which may be due to the irregular pattern of tourists visiting the country. Therefore, this study provides important baseline research with the scope of extending to each South Asian country individually to perform detailed uncertainty analysis to assess the roles of GDP, population growth, vehicular growth, tourist growth and other economic factors in their changing patterns of fuel consumption and subsequent N$_2$O emissions, which is not feasible to cover in detail in this study.

Sector-wise, most of the economic sectors depicted moderate uncertainty except agriculture, and others which exhibited a high level of uncertainty

Figure 6. Temporal profile of N$_2$O emissions showing major contributing sectors for Bangladesh, India, Pakistan and Sri Lanka over the time period of 1990–2017.
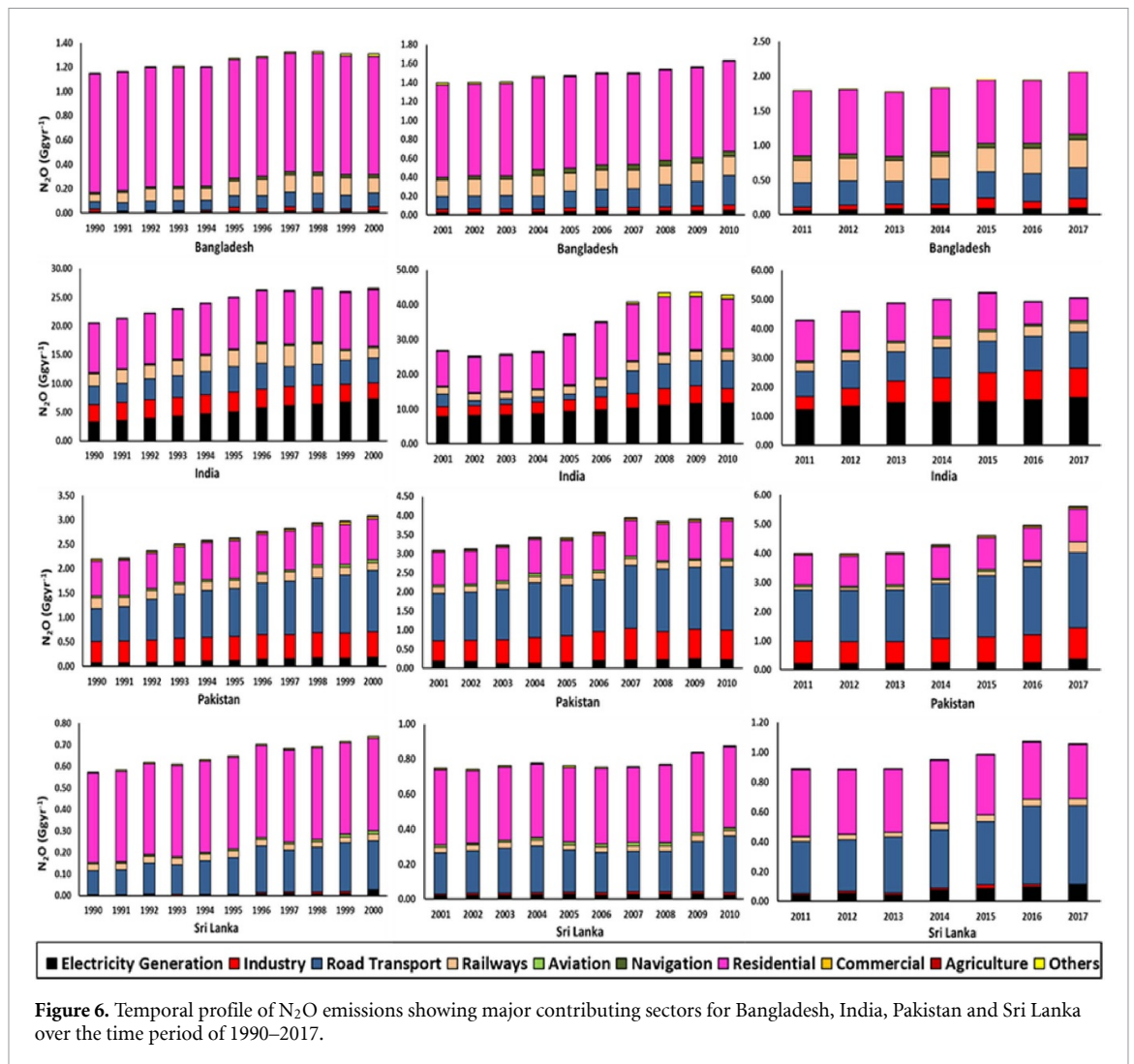
due to the large data gaps in fuel consumption for these categories in most of the South Asian countries (table 4; supplementary information table 3). The problem is further compounded by the lack of consistent and updated country-specific sector- and technology-based EFs making it difficult to improve the results by the adoption of high tier methodologies. Therefore, under the current scenario, it is suggested that all South Asian countries, especially the less developed and low populated countries like Afghanistan, Maldives, Bhutan and Nepal, should promote capacity building to collect and maintain reliable, consistent and long-term source- and technology-based fuel consumption national datasets in all sectors. South Asian countries should also invest towards updating the EFs in line with changing sector-/country-wise fuel types and combustion technologies to develop country-, sector- and technology-specific EFs. Besides, all South Asian nations should maintain data transparency among each other and make reliable data available in the public domain to facilitate better regional and international cooperation for sustainable N management and the adoption of higher-level tiers (tier II and

tier III) of N$_2$O estimation to reduce ambiguity in emissions.

4. Future emission projections and policy implications

BAS is the pessimistic scenario with increased energy consumption leading to a rise in emissions over time by the continuation of the current policy interventions/new energy technologies incapable of arresting the change. In contrast, South Asian N$_2$O emissions from the residential sector are expected to reduce to 71% under BAS by 2041 with the adoption of cleaner and more efficient fuels like LPG rather than fuelwood. The Pratyaksh Hanstantrit Labh Yojna scheme 2013 (MoPNG 2013), of the Indian Government, in rural areas is one of the important policy interventions implemented in this direction. It provides subsidies to purchase LPG directly into women's bank accounts for easy access to clean cooking. In the long term, the mitigation scenario will further assist in the reduction of residential N$_2$O emissions by another 8% by 2041, as compared to BAS, via promoting the
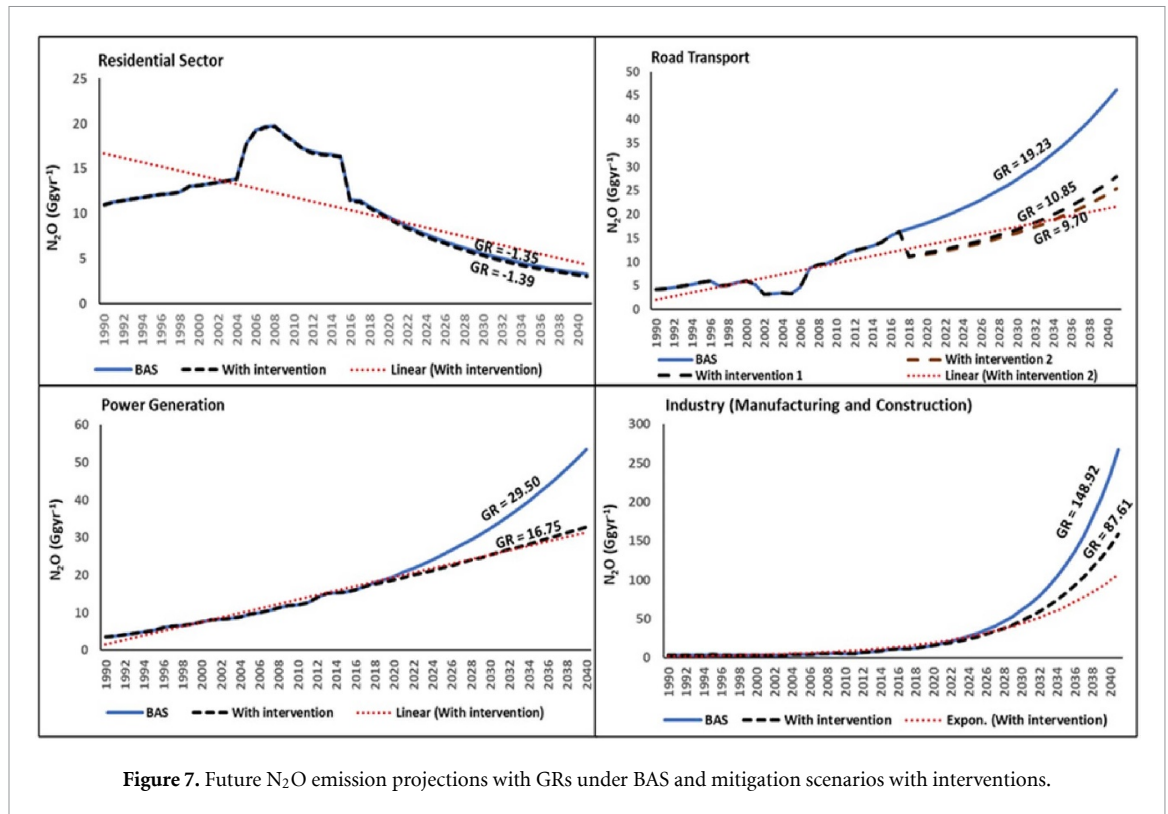
Figure 7. Future N_2O emission projections with GRs under BAS and mitigation scenarios with interventions.

intervention of solar powered induction stoves in the region (figure 7).

Apart from the residential sector, BAS holds true for the road transport, power generation and industry sectors as N_2O emissions are expected to increase by 2.8, 3.3, and 23.9 times their 2017 estimates, respectively, indicating the inability of current policy options to arrest their growth. In the transport sector, N_2O emissions are mostly due to augmented diesel consumption in the road sector. Stabilising the use of other fuels and switching 51% of diesel consumption to cleaner fuels like CNG can help to reduce N_2O emission to 39% by 2041 under the projected mitigation scenario (intervention 1, figure 7). But dependency on limited policy options may decelerate the N_2O savings in the long run. Therefore, various policy interventions proposed by the South Asian countries such as the National Electricity Mobility Mission Plan of India, 2020 (MoHIPE 2020), the Transport Integrated Strategic Vision of Bhutan, 2040 (TNC, Bhutan 2020), the National Electric Vehicle Policy of Pakistan (MoCC 2019), etc are directing the inclusion of electricity driven vehicles/metro rails and their manufacturing in the South Asian region as one of the potential N_2O mitigation options in the transport sector in the near future. The present study also points out that switching 51% of diesel and 50% of CNG vehicles to electrified and hybrid vehicles (intervention 2, figure 7) may lead to enhanced N_2O emission reductions to 45% by 2041. Thus, policies encouraging major shifts towards electrical and hybrid vehicles in road transport across South Asia can further augment long-term N_2O emission decelerations.

The N_2O emissions from power plants and industries are mainly from coal combustion. The emission savings from electrical vehicles may be offset by the amplified coal usage in industry and power plants, until it is linked tightly with policy interventions. The use of natural gas for power generation and industries is also expanding in the region, to avert the emissions, but replacing fossil fuels with renewables is the best option in the long term to achieve net zero emissions. In this direction, the Indian government has proposed a new NDC scenario to encourage the share of renewables in power generation to be 22% by 2032, particularly solar, hydro and wind energy. If we extrapolate this scenario for the entire South Asian region by replacing 22% of coal consumption with renewables in the power and industry sectors, with the stable use of other fuels, N_2O emissions can be reduced by 41% in both the sectors. In addition to the Indian NDC scenario, the Energy Policy of Bangladesh, 2008 (TNC, Bangladesh 2018), the Scaling Up Renewable Energy Programme of Maldives, 2015 (MEE 2016), the Alternate and Renewable Energy Policy of Pakistan, 2019 (MoWP 2019), the Renewable Energy for Rural Economic Development Project of Sri Lanka, 2008 (SNC, Sri Lanka 2011), and the Development of Solar Cities Programme of India, 2015 (MNRE 2015), are some of the major future directives to support the use of renewables in this direction. However, the use of renewables is highly cost intensive and may not happen soon enough. To make it happen in real terms in the region, the strict enforcement of various current and future policy interventions, and

providing tax incentives and financial support for research and development of renewable energy, is mandatory.

5. Conclusions

The present study envisages the utility of updated and improved regional N_2O emission quantification for sustainable Nr management. Fuel consumption regulates country-wise N_2O totals. The hierarchy of fuel consumption and the resulting N_2O emissions largely reflect the sheer size/population of each country. Therefore, India, Pakistan and Bangladesh define the overall South Asian N_2O trends and together account for more than 95% of the total South Asian fuel consumption, releasing about 94% of total N_2O emissions. Temporal variability in N_2O emission in South Asia has shown a reduced growth of 147% in Indian N_2O emissions compared to small countries like Bhutan and Maldives. This is because fuel consumption in India has stabilised during the period 1990–2017, with a CAGR of only 4%, whereas fuel consumption in Bhutan and Maldives has increased at a CAGR of 10% and 8%, respectively, over time. This temporal energy use change in Bhutan is mainly driven by strong energy demand in the industry, transport and building sectors, while power generation and booming tourism has contributed substantially towards rising fuel consumption in Maldives. Therefore, as compared to agriculture, high fuel consuming sectors including power, industry and transport are most likely to drive future N_2O emission in the South Asian region in the absence of suitable mitigation options.

Further, sectoral estimates are controlled by the variety/types of fuels, their respective heat content and EFs, along with rising fuel consumption. The residential sector emitted the greatest N_2O at the sectoral level but witnessed a decrease of 71% over time due to enhanced LPG consumption. Switching diesel- and CNG-driven vehicles with electric and hybrid vehicles can help to save N_2O emissions by 45% in the road sector, whereas the replacement of coal with renewables in the power and industry sectors will lead to 41% N_2O decelerations from both the sectors by 2041. Thus, fuel switching, supporting the replacement of more polluting fuels with more energy efficient and clean fuels, must be the main strategy to bend the curve of rising N_2O emissions.

In conclusion, this study for the first time provides an updated and detailed country-wise sectoral N_2O emission inventory for the South Asian nations to enable policy makers to devise the right mitigation measures to arrest accelerating N_2O emissions. Further, such an assessment of the regional realities of implemented policies holds immense potential to guide South Asian countries to boost their emission reductions, committing to the Paris Climate Accord and 17 UN sustainable development goals targeted for 2030 and beyond.

Data availability statements

Suitable data sources related to fuel consumption and emission factors that support the findings of this study are included within the article along with important links and the detailed datasets for country-wise N_2O emission estimated from different sectors of South Asia provided in the supplementary information.

The data that support the findings of this study are available upon reasonable request from the authors.

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