The effect of greenhouse gases and black carbon aerosols on global warming

Atiq Ur Rehman* **Muhammad Akber Ishfaq Ahmad and Waseem Sardar**

Abstract. Since the start of the industrial revolution and due to the human activities, that is, burning of fossil fuels, oil and gas, the so-called anthropogenic greenhouse gases concentrations have been increased in the earth atmosphere. Similarly, black carbon aerosols have a direct and indirect effect on global warming and have the potential to absorb solar radiation and thereby affect the earth climate. Therefore, black carbon aerosols play a critical role in the climate system. The increasing warming of the planet earth has caused climate change, that is, droughts and floods, to name a few. Our object is to examine how global warming responds to the increasing magnitude of greenhouse gases and black carbon aerosols using both univariate and multivariate generalized additive models (GAM). We have considered the data for all the countries over the world. We concluded that with the increasing trend of greenhouse gases and black carbon aerosols, the world temperature is also increasing.

Key words and phrases: Global warming, Greenhouse gases, Black carbon aerosols, GAM model.

1. INTRODUCTION

Climate change is the most alarming issue that we are confronting today in the whole world. Climate change poses significant risks for a range of human and animal systems. It is widely accepted that due to the ticking-upward temperature, the glaciers are melting. One example is of Himalayan glaciers explained by Immerzeel et al. (2010). These glaciers are melting not solely in the Himalayan region but also in other parts of the world, largely in Antarctica and Greenland, are directly contributing to the rising sea level. According to Nicholls & Cazenave (2010), with rising sea level, the coastal land would get flooded; the ocean saltwater would mix-up with the groundwater. Drought, another effect of climate change, is a long-term low rainfall and water shortage, also known as the dry spell or dry weather. It has many consequences, chief among those is a lack of food due to the low level of rainfall farmers are unable to food, e.g. crop yield. Second, some plants (help in absorbing the CO_2 in the atmosphere (Griscom et al., 2017), a greenhouse gas explained in more detail later) can die out because of the lack of water and thereby increase the global warming. Some of the other impacts of climate change are on biodiversity (Bellard et al., 2012), food security (Wheeler & Von Braun, 2013), global health (Louis & Hess, 2008), and global agriculture (Calzadilla et al., 2013) to name a few.

Climate change is closely coupled with the rising mean temperature of the

*To whom correspondence should be addressed.

world for many decades. Due to the human activities, particularly, burning of fossil fuels for producing energy, the global temperature has been increased by 1°C compare to the pre-industrial revolution. Moreover, it is more likely that temperature will reach 2.4-6.4°C by the end of 21^{1st} (Change, 2014). This increasing temperature is also known as global warming, which is not natural but human-driven.

There are number of greenhouse gases that cause global warming, among which, three of them cause more then half of the greenhouse effect (Liu et al., 2019) are Carbon Dioxide (CO_2) released by the usage of fossil fuel; burning of other solid waste and plant wood. It is considered as the principle anthropogenic greenhouse gas that effect the earth's energy balance. Other greenhouse gases are Methane CH_4 and Nitrous Oxide N_2O. The later two gases are short-lived but have more global warming effect compare to the CO_2.

Black carbon aerosols, a short-lived climate forcing factor, also known as soot that effectively absorb solar radiation, thereby effect the global warming (see Ramanathan & Carmichael (2008)) and change the melting of snow and ice cover (Bond et al., 2013). It is emitted by both human (e.g different combustion processes) and natural (wildfires). It is true that from burning of the fossil fuel and biomass, the chemical compositions of the earth's atmosphere is changed a lot; that is, greenhouse gases as well as carbon aerosols are increasing drastically since the industrial revolution in the eighteenth century and onward.

There are number of studies that have found relation among the global warming, greenhouse gases emissions ad air pollution. For instance, Attanasio (2012); Attanasio et al. (2012) proved that anthropogenic forcings (but not natural forcings) is the main cause of increasing global warming. On the other hand, Stern & Kaufmann (2014) used the Granger causality tests and found that both natural and anthropogenic forcings cause temperature change; furthermore, the reversed is also true means temperature can cause changes in GHG. Stips et al. (2016) have examined the global radiative forcings and global mean surface temperature anomalies. It is shown that the GHG emissions is causal drivers of global warming; aerosols are, comparatively, smaller but significant driver of global warming. Other studies Fyfe et al. (2013); Xiao et al. (2020) related to one specific region (the Arctic region), both with consistent results, have also shown that Arctic mean surface temperature is increased by GHG but aerosols helped cooling the Acrtic surface. Undorf et al. (2018) have also shown the regional cooling effect of emissions of Europe and North America aerosols on Eurasia.

Our object in this paper is to find out whether greenhouse gases and black carbon (BC) aerosols effect global warming using both univariate and multivariate generalized additive models using the data of all the countries around the world.

2. METHODS

2.1 Variables of interest and data sources

In this study, we are considering yearly data of countries all over the world. However, based on the data availability some countries (or Islands) are excluded. To examine the interrelation, The variables are: annual average Temperature data (from 1901-2012) taken from the World bank using an R package "rWBclimate" Hart (2014); greenhouse gases, which is Carbon Dioxide, Methane and Nitrous Oxide; and air pollutant, that is, Black carbon aerosols from Emission Database for Global Atmospheric Research (EDGAR) (Crippa et al., 2019). The data of greenhouse gases and black carbon aerosols are available for 1970-2015. It is worth noticing that it is not determined that the warming of early 20^{th} century is caused by anthropogenic activities (Hegerl et al., 2018). Thus it is good to consider the 2^{nd} half of the 20^{th} century for examing the global warming caused by anthropogenic activities.

As there are three variables in the greenhouse gases, we have combined these variables using global warming Potential (GWP), which can be defined as relative to the Carbon Dioxide and given a period of time how much one ton of gas will absorb the energy. For example, according to IPCC fifth assessment report Myhre et al. (2013) one ton emission of Methane energy absorption is equivalent to 34 ton Carbon Dioxide for a 100-year timescale. Similarly, the energy absorption of one ton Nitrous Oxide is equal to 298 ton of Carbon Dioxide for 100-year timescale. The GWP is also known as Carbon equivalent emissions and thus GWP for Methane is 34 and 298 for Nitrous Oxide. To make it Carbon equivalent, we simply multiply each greenhouse gas with their respective GWP value and add them up, note that GWP value for carbon Dioxide is equal one.

2.2 Generalised additive models

It is possible that some covariates have non-linear relationship with the response variable, in this case without variable transformations, to make the functional form linear, applying generalized linear models (GLMs) can give misleading results as GLMs are only applicable when linearity assumption holds. Thus Generalized additive models (GAMs) were introduced (Hastie & Tibshirani, 1990; Wood, 2006), which is the extension of GLMs that relax the assumption of linearity, provide more flexibility and allowing for handling various types of data. The key advantage of GAMs is that, unlike GLMs, it can automatically handle non-linear, monotonic or more complex relation between response and predictors without the use of variable transformations or the use of predictors polynomial terms. The GAMs works in a way that it includes smooth basis functions for fitting wiggly curves (or surfaces). These models can be used in more complex relation of response with the predictors that cannot be fitted by common linear and non-linear models. In other words, GAMS is used to estimate the smooth functional relationship between covariates and response (Pedersen et al., 2019). The functional form of GAMs is as follows:

$$g(E(y_i)) = \underbrace{\beta_0 + \sum_{j=1}^{n} \beta_j x_{ji}}_{\text{Parametric part}} + \underbrace{\sum_{k=1}^{n} f_k(x_{ki})}_{\text{Non-parametric part}} + \epsilon_i. \tag{2.1}$$

The above equation is the GLMs (parametric part) coupled with the non-parametric part makes it generalized additive models, which is semi-parametric models. The f_k are the smooth basis functions of some non-parametric predictor covariates. Where ϵ_i is the ith residual assumed to be normally distributed with variance σ^2. GAMs are Non-parametric in a way that, unlike linear and non-linear models, there is no pre-decided functional form of the model but constructed based on the data given to them [GAMs]. Moreover, according to Guisan et al. (2002), finding suitable polynomial terms and transformations of the predictors to best fit the linear model can be time-consuming and imprecise. GAMs model have the ability to find the proper polynomial terms and transformations for the predictors.

The GAMs can also be extended to multivariate case that is used to explain the relation between more than one response variables and predictors. For example, we have three variables, that is, temperature, greenhouse gases and air pollution as response variables with the same set of predictors (mentioned below). The joint generalized additive model for all responses can be estimated, which is used in Gordon et al. (2018). It is also possible to use a common way of estimating separate model for each response variable ignoring the joint correlation among the response variables. But a common drawback of estimating individual models is that, given that there exist a correlation among the response variables, they will have less predictive accuracy compare to the multivariate model (Breiman & Friedman, 1997). A multivariate regression models can be used when there is a correlation among the dependent variables (Hartung & Knapp, 2014).

In this paper, we are fitting four GAMs: three univariate and one multivariate. In the first three univariate models the y_i denotes the annual average temperature, Global warming potential index and black carbon aerosols of all countries. The covariates are same for all these four models. The smooth function is applied on all the covariates included in the models: smooth function of time (measured in years) to fit for the non-linear time trend; smooth function of longitude and latitude, which are the spatial coordinates of each country to account for spatial trend with "Duchon splines" and is used to control for spatial auto-correlation in the residuals, that is, $s(longitude, latitude)$; and estimating separate smoothers for each country over time, we have used smooth function with "factor smoothing interaction" spline. Note that, as mentioned before, for annual average temperature the yearly data is from 1901-2012 and for global warming potential index and air pollution is from 1970-2012. To estimate our GAMs, we have used a well-known R package "mgcv" (Wood & Wood, 2015).

3. RESULTS AND DISCUSSION

The smooth splines are not easily interpretable due to the reason that for each bases function there are different coefficients. For example, if $k = 10$, number of knots, it means there are 10 bases functions each with different coefficient attached. Therefore, rather a table of coefficients we have presented a graphical representation of GAMs.

To interpret the univariate GAM here time (year) being a predictor variable of temperature, subplot in Figure 1 named as Temperature shows that mean global temperature is increasing shown with the 95% confidence interval. Generally, the 1901-20 phase is the period of stagnation, from 1921-80 there is a slight increase in the temperature, and afterwards there is a clear phase of accelerated warming as clear from the report Sanchez-Lugo (2019) that since 1981 the average rate of temperature is more than twice. Furthermore, if we look at the figure more closely it can be seen by inspection that two exceptional warming periods of the 20^{th} century, that is, 1925-1944 and 1978-1997 (Jones et al., 1999) can also be seen with increasing trends compare to the others in the subplot Temperature. The early 20^{th} century warming episode was mostly natural origin (Stott et al., 2000). In contrast, a multidecadal cooling period, 1940-1975, (Fyfe et al., 2016) is also clear known as big hiatus. Note that the short fluctuation in the temperature is due to the natural climate variability as shown by Easterling & Wehner (2009), the natural variability as long as a decade or two of warming or cooling is the part of longer term global warming.

We have also estimated separate smothers for every country in the world. This means that for each country there is separate intercept and slope being estimated in which few more-economically developed (plus developing) and industrial countries are shown in figure 2. It can be seen that in every developed country shown in figure 2, there is a slight increase in the temperature over given period of time (a positive approximately linear relationship), but this small increase in temperature can make big contribution to the global average temperature, thus increase the overall global temperature and cause global warming. Moreover, the intercept term is different for each country, for example, the intercept of Japan lies near 16°C while United States intercept lies above 18°C. These non-identical intercept is due to: the distance from the equator; the distance from the ocean; and the height above sea level aka altitude.

The second univariate model where global warming potential index is a response variable has positive almost linear relationship with the time (year) as a predictor variable shown in figure 1 subplot log(GWP index). Note that there were four outliers, which is been removed prior to the estimation of the GAM model. It can be seen that there has been continuous increase in the magnitude of greenhouse gases emissions since 1970 due the combustion of fossil fuel, industrial processes and other contributors such as deforestation and agriculture. To examine the carbon equivalent (CO_2e) emissions of the individual countries, the separate smothers are plotted figure in 3 on the log scale. Since the United States and China are the greatest emitters of greenhouse gases the y-axis scale is same for both the countries but different from the rest of the countries plotted due to the low emissions, comparatively. We have plotted five countries of G20 (group of 20 largest economies) and China, which are the top emitters of CO_2e. United States is the largest emitter of the greenhouse gases shown in subplot "United States" in figure 3. However, since 1970 emission is gradually declining over a given period of time. The reduction in emission is true as shown by Houser & Pitt (2020), they have used the data of 1990-2020. China's emission is increasing gradually but a dramatic growth can seen since 2000. Future projections shows that China's greenhouse gases emissions will continue to grow (Nakicenovic et al., 2000). Compare to United states and China, India is third largest emitter of greenhouse gases and since 1970 the emission growth is increasing. Similarly, Indonesia's emission is also growing. There is some fluctuations of increasing and decreasing in 20^{th} century. The last two countries, Germany and Japan, greenhouse gases emissions are declining but, unlike Japan, Germany's emissions is decreasing significantly.

With respect to Black carbon aerosols considered as response variable and removing three outliers before estimating the model. It can be seen from figure 1 subplot log(BC) that the magnitude of Black carbon aerosols are positively associated with the time (Year) as a predictor variable. Black carbon aerosols are increasing rapidly in the first two decades and then since 1990 gradual increase can be seen.

Black carbon aerosols for most polluted individual countries due to the industrialization and urbanization are plotted in figure 4. It can be seen that the

United states is the most contaminated country that emissions is much greater than other countries of BC aerosols. However, In United States its magnitude is decreasing since 1970. For China, for 1970-2000 there was a little increase in BC. However, after 2000 a considerable increasing trend can be observed. There was almost unchanged magnitude for Brazil but compare to the rest of the countries (data not shown) except United States and China its emission is very high in the given period of time. Furthermore, for India, the trend was almost constant in the first three and a half decades, that is, 1970-2005; however, considerable increase in contamination of BC can be seen in the last ten years.

In multivariate GAM model shown in figure 5, results is almost similar to the univariate GAM models (in case of temperature if we take a look from 1970 and onward). With respect to temperature, the overall increasing trend has been observed and the fluctuation is due to the natural climate variability as mentioned above. Similarly, the emission of the greenhouse gases (can be seen in figure 5 subplot Log(GWP index)) and black carbon aerosols (subplot Log(BC)) is also increasing over given period of time.

4. CONCLUSION

Our results clearly show that the global average temperature is increasing from the beginning of the 20^{th} century. But with the close examination of the temperature, we have observed that there was a multidecadle cooling episode in the 20^{th} century, that is, 1940-1975 and this cooling period is known as big hiatus. Furthermore, Two episodes of warming periods is also observed in the previous century, 1925-1944 and 1978-1997, the early period was mostly natural origin. The substantial increase in the temperature's rate took place almost since the 1990. The temperature of the individual countries was slightly increasing over a given period of time (except some countries) but these small increase in temperature of each country have given rise to the global average temperature and cause global warming. It is worth noticing that there is a lot of difference among the individual country temperature, which is due to the distance of country from the equator and ocean, and altitude.

In case of global warming potential index, our results indicate that since 1970 the greenhouse gases emissions is increasing steadily due to the combustion of fossil fuels and industrial processes etc. For individual countries (results are shown for some of the developed countries) we found that there was large emission of greenhouse gases in the United States but declining gradually. China, second largest economy, was the second largest emitter increasing slowly till 2003 but has shown significant increase after 2003. The emission of India and Indonesia is also increasing. However, Germany and Japan have shown significant reduction in the emissions of greenhouse gases.

For Black carbon aerosols, according to our results there was rapid increase in emissions in the first two decades but gradual increase since 1990. In case of individual countries, the results are shown for United States, China, Brazil and India. These countries are the largest emitter of BC aerosols. Particularly, United States is the most contaminated and largest emitter; however, decreasing trend is observed since 1970. China is the second country with the greatest emission is also increasing followed by Brazil and India.

In case of multivariate GAM, with the increasing trend of greenhouse gases and black carbon emission the global surface temperature is also rising. Thus we can conclude that there is positive relation among global warming, greenhouse gases and black carbon aerosols. Reducing emission of both greenhouse gases and black carbon aerosols will slow the rate rising global temperature.

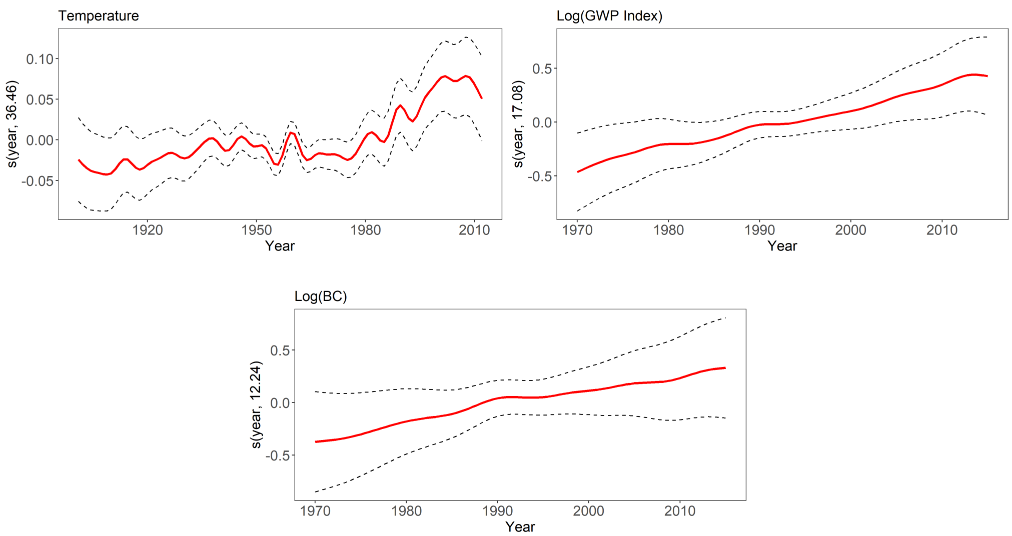

FIGURE 1. *Smooth term plot of three individual GAM models for Temperature, Global Warming Index and Black carbon as reponse variables and Time (Year) as a predictor variable.*

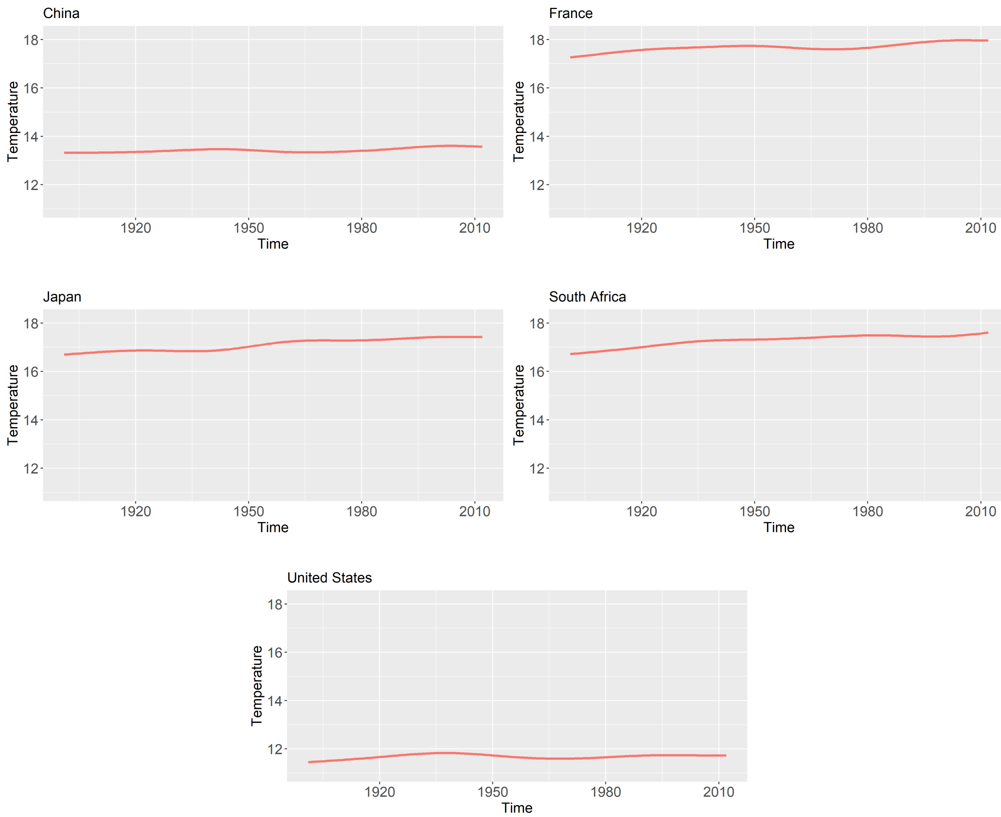

Figure 2. *The smoothing plots of temperature for individual developed and developing countries.*

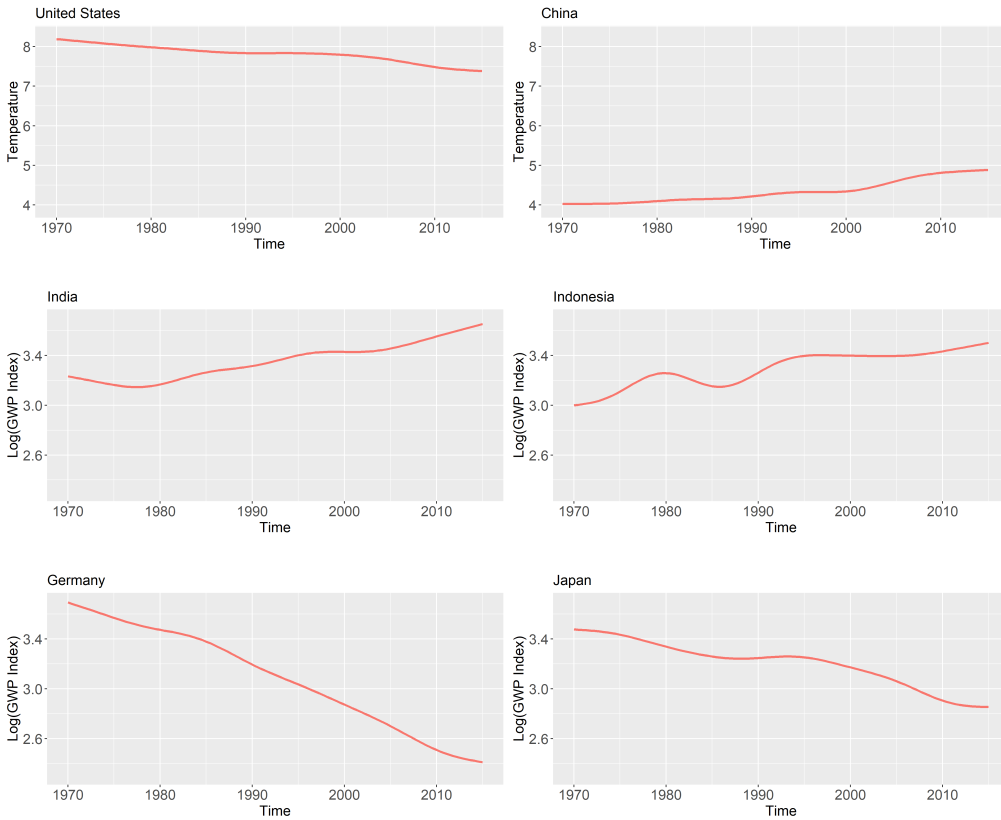

FIGURE 3. *Greenhouse gases emissions for individual developed countries in terms of global warming potential.*

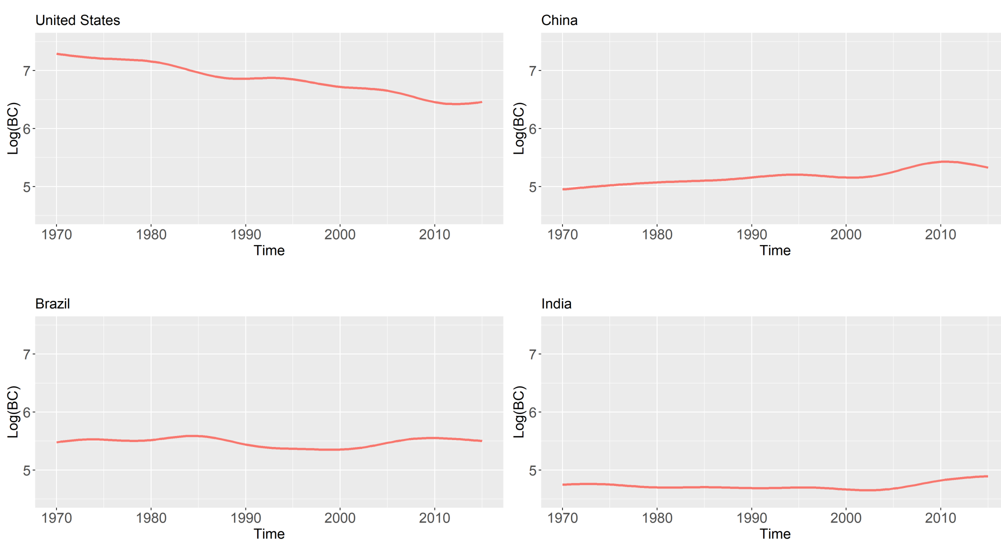

FIGURE 4. *Black carbon emissions, $PM_{2.5}$, for the most contaminated individual countries.*

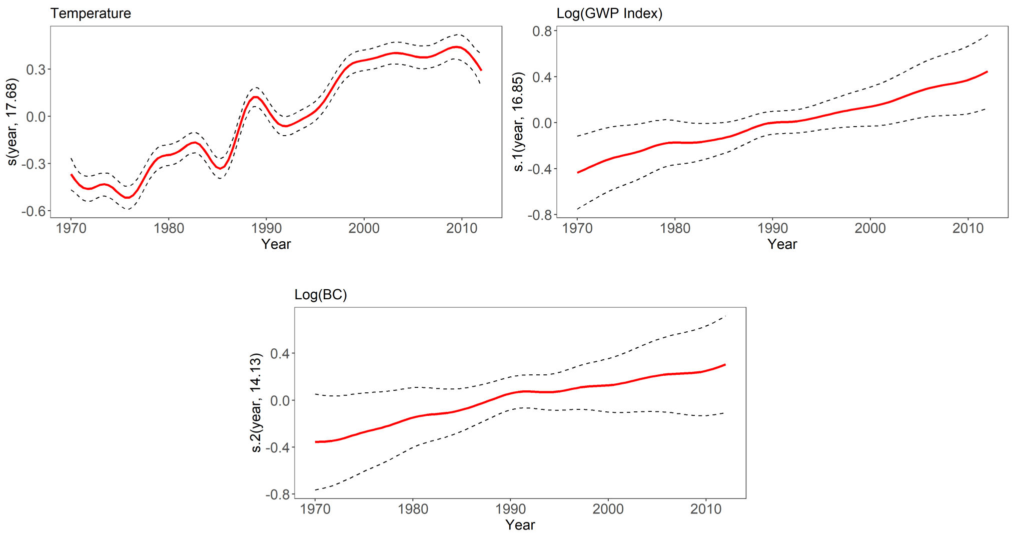

FIGURE 5. *Multivariate generalized additive model with three equations plots: Smooth term for temperature, global warming index and Black Carbon with Time (Year) as a predictor variable.*

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