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How Precisely «Kaya Identity» Can Estimate GHG Emissions: A Global Review

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Abstract

Climate change is the greatest environmental threat facing our planet, endangering health, communities, economy and national security. Many models tried to evaluate influencing factors, estimate emission rates or any parameter can effect on this phenomena. «Kaya identity» is a mathematical equation that relates economic, demographic and environmental factors to estimate anthropogenic emissions in global scale. In the present study, «Kaya identity» is developed for 215 countries around the world (national scale) during 1990-2011. Then model predictions are compared with real data to evaluate how well Kaya identity can estimate emissions and how results accuracy changed over time. Based on the results, energy intensity and carbon intensity follow a decline; population and Gross Domestic Product (GDP) per capita follow an increasing path. More than 80% of emissions, about 74% of GDP and 52% of the population around the world can be estimated precisely (< 20% error) by Kaya identity. The model predictions show an improvement in accuracy of results over time. Eight out of top ten emitter countries could be estimated well (usually between -20% < error < +20%) by Kaya identity from emission point of view. Results confirm that Kaya identity can be used widely and reliably for estimation of emissions and identification of effective factors globally to help in achieving emission reduction targets by helping governments to better predict emission rates.

Keywords: Climate change, Emission, Kaya identity, Accuracy, World.

1. Introduction

During the past decades, a distinct body of researches has started to investigate the relationship between climate change impacts and human influences on the climate system. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that human activities, with more than 90% certainty, are responsible for «most of the observed increase in globally averaged temperatures since the mid-20th century» (IPCC, 2007a). These activities would lead to emission of four principal greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the halocarbons. Accumulation of these components in the atmosphere will cause significant effects on global temperature, weather, food security, water supply and will take its toll on the economy (Tavakoli et al., 2016). People are affecting climate, primarily through emission of greenhouse gases from fossil fuels and other resources. As a consequence, climate change can impact on almost all aspects of human lives. Global warming and higher temperature, sea level rise, increased risk of drought, fire and floods, stronger storms and increased storm damage, changing landscapes, posing risks to wildlife, more heat-related illness and disease, economic losses and many other challenges are some of direct and indirect effects of climate change. Many researchers believe that industrial revolution is the origin of human influences and emission increase. Currently, combustion of fossil energy resources for heat supply, electricity generation and transport, account for around 70% of total Greenhouse Gases (GHGs) emission (IPCC, 2007b). As a result, concentration of GHGs have been rising rapidly (2.3 ppm CO_{2eq} per year). The concentration of CO_2 increased to 408.84 ppm in June 2017 from 280 ppm during pre-industrial era (NOAA, 2017).

The unequivocal scientific evidence in combination with recent extreme events (De'Donato and Michelozzi, 2014; Duchez et al., 2015; Sena et al., 2014) for changing and warming of the climate system has taken this environmental challenge as a center stage in the international debates. Recent studies show that if a limit is set to the total amount of CO_2 emitted globally until 2050 (global carbon dioxide budget), there will be a realistic chance for restricting global warming to 2 °C (Friedlingstein et al., 2014; Kvale et al., 2012; Messner et al., 2010). It is obvious that countries cannot continue to emit carbon dioxide as they did in the past and a 450 ppm CO_{2eq} stabilization target suggested and should be placed as the upper limit on concentrations of heat-trapping emissions to avoid dangerous climate change (Luers et al., 2007). Consequently, international climate efforts have been focused on emission reduction targets to stabilize GHG emissions at a safe level in the atmosphere and a group of studies are analyzing the important factors influence on GHG emissions.

Identifying the factors which influence on carbon emissions is highly challenging because of the wide number of these driving factors. Clearly, population is one of the

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most important ones. Population growth affects the energy demand to supply essential requirements, such as food, water, clothing, shelter, and so on. Birdsall (1992) explains that by two different mechanisms, population growth could contribute to greenhouse gas emissions. At first, an increase in fossil fuel emissions because of more demand for energy by different sectors such as power generation, industry, transportation and so on. At the second, deforestation, land use and combustion of fuel wood which decrease the potential ability of the environment to absorb existing GHG emissions and strongly influenced by the population increase. Many researchers investigated this relationship (Begum et al., 2015; Bin and Dowlatabadi, 2005; Druckman and Jackson, 2009; Sadorsky, 2014; Zhu and Peng, 2012). In addition, economic development pattern can be considered as the other key factor which influence carbon emissions, especially for developing countries. Developing countries carry out this pattern of development relying on fossil fuels while lack of appropriate or commercialized technologies, high initial capital investments and no substantial outside expertise to operate are some of the obstacles the developing countries are faced with. Many researchers have been studying issues related to economic development, fossil fuel emissions or Environmental Kuznets Curve (EKC) (Du et al., 2012; Fodha and Zaghdoud, 2010; Ghosh, 2010; Lotfalipour et al., 2010; Menyah and Wolde-Rufael, 2010; Ozturk and Acaravci, 2010; Pao and Tsai, 2011). The other factors, such as welfare level, affluence, fuel type, buildings size, industries type, and climate circumstances, can be effective on the rate of GHGs emission in a country or region. In order to evaluate emissions of different regions and effective driving factors, comprehensive and measurable parameters should be examined. Many conceptual and mathematical models are suggested and developed for this purpose.

The «Kaya» equation is a conceptual framework employed to characterize the various driving forces of anthropogenic GHG emissions at a global scale. These factors cover demographic, economic, fuel type and energy usage to estimate potential CO_2 emissions. To date, few studies have explored this equation at sub-national or regional scale to predict emission rates or analyzed the most effective influencing factors for mitigation efforts (Duro, 2010; Jung et al., 2012; O'Mahony, 2013; Zhao and Wu, 2010; Ziemele et al., 2015). To the best of our knowledge, no attempt has yet focused on all world›s countries at a national scale, considering all four driving forces.

Kaya Identity, which was developed by Yoichi Kaya (a Japanese energy economist), is meant to estimate global (not national) emissions of CO_2. Therefore, it is interesting to see how it could be downscaled to a national level. The manuscript is novel in the way it applies «Kaya Identity» to individual countries around the world (in the case of data availability) and examines how well Kaya equation can estimate emissions in compare with real data. For this purpose, the expected emissions data for a period of 20 years (1990-2011) are estimated and compared with real data at this period. It seems that despite simplicity and inaccurate appearance of Kaya identity; it has a great potential to estimates CO_2 emissions close to real data.

2. Methodology

A powerful model, extensively used to conduct quantitative analysis on CO_2 emissions, is «Kaya Identity» which was introduced by the Japanese professor Yoichi Kaya during a seminar organized by IPCC in 1989 (Kaya and Yokobori, 1997; Yoichi, 1989). This model established a simple mathematical equation which relates various economic, demographic and environmental factors to estimate global CO_2 emissions of human activities as below:

$$E_{carbon} = Population \times \frac{GDP}{Person} \times \frac{Energy}{GDP} \times \frac{CO_2}{Energy} \tag{1}$$

where,

E_{carbon}: Carbon emission rate (GtC/yr)

$\frac{GDP}{Person}$: Per capita Gross Domestic Product (\$/person-yr)

$\frac{Energy}{GDP}$: Energy intensity, primary energy per unit of GDP (EJ/\$)

$\frac{Carbon}{Energy}$: Carbon intensity, carbon emissions per unit of primary energy (GtC/EJ)

In more details, this emission equation offers a framework for evaluating the factors shaping GHGs emission, in the form of fuel consumption. The GHGs resulting from fossil fuels combustion (CO_{2eq}) is the function of the amount of fuel consumption and fuel type which the first one itself can be affected by population, economic development pattern, welfare level, fuel dependency of industries, climate circumstances of region and so on.

Population growth is one of the major factors that lead to carbon emissions in all countries; however this impact has been more pronounced in developing countries than the developed ones.

The world population increased from 791 million in 1750 (the beginning of Industrial Revolution) (UN, 2004) to 7.4 billion at the end of 2015. During this period, the people who just started burning of fossil fuels increased carbon dioxide concentrations from about 280 parts per million to 408.84 parts per million in June 2017.

For Kaya Identity, the economic situation of society can be estimated by Gross Domestic Product (GDP) per capita. GDP per capita is a measurement of the total economic output of a country divided by its population and provides a general index for standard of living. This index mostly used for international comparisons. Countries with low GDP per capita and slow growth in GDP per capita are less able to satisfy basic needs for food, shelter, clothing, education, and health (Tucker, 2012) and therefore, this index is a measure of fossil fuel consumption in a society, hence the GHG emissions.

Energy intensity is a measure of the energy efficiency of a country›s economy. In other words, this index is a measure of the amount of energy it takes to produce a dollar›s worth of economic output, or conversely the amount of economic output that can be generated by one standardized unit of energy. Some factors, such as the level of industrialization, the mix of services and manufacturing in economic structure of a country, and the attention paid to energy efficiency, can change the amount of this index (Wang et al., 2005; Wang et al., 2015).

Carbon intensity is the relative amount of carbon emitted per unit of energy or fuels consumed. It is a measure of how efficiently countries use their polluting energy resources, such as coal, oil and gas. The countries which are ramping up the amount of renewable energies can decrease the carbon intensity but those who still rely on fossil fuels to drive economic growth have less chance for reduction. As a real example, among the top 25 emitter, China had declined its carbon intensity about 51% over 12 years (1990-2002) but carbon intensity rose significantly in Saudi Arabia, Indonesia, Iran, and Brazil (Baumert et al., 2005).

Population and economic growth are considered as ascending factors for emissions. In return, for the world as a whole, energy intensity and carbon intensity are both improving over time, which may help offset some of consequences associated with population and economic growth.

To achieve the goal of the present work, five types of information include population, GDP, energy intensity, carbon intensity and CO_2 emissions from fossil fuels are needed. Population censuses are collected from World Population Prospects- the 2015 revision (UN, 2015). Information related to economic output of countries, such as GDP (constant 2005 US$) and carbon intensity received from the World Bank- World Development Indicators website.

Besides, energy intensity information is calculated based on data provided by U.S. Energy Information Administration (EIA). To determine the amount of real GHG emissions, the amount of all fuel types consumed in a specific country or region are to be estimated. Then, using the emission factors for each fuel, the relevant GHG emissions are determined. In the final step, using the Global Warming Potential (GWP) coefficients, the emissions report based on carbon dioxide equivalent (CO_{2eq}). During the present study, the data related to CO_2 emissions from fossil-fuel burning are received from Carbon Dioxide Information Analysis Center (CDIAC), World Bank Data Center and for some cases, emissions are estimated from fuel consumption data of each country and IPCC 2006 guideline is used for the calculation of emissions.

The amount of CO_2 emissions is estimated by original Kaya Identity as mentioned in equation 1. In this way, no coefficient or special function is considered in the calculations. This calculation includes a period of 20 years (1990-2011) and for about 251 countries around the world. Then, calculated emissions are compared with real data to estimate how successful Kaya Identity to estimate GHG emissions is. It means that the gap between actual and predicted values by the model is evaluated and expressed as percentages. For each year, separate calculations are done. In fact, one year›s steps are considered for each region or country to evaluate this difference. In the present study, Excel 2013 and SPSS 16 software (for calculations and error estimation of the model) and ArcGIS 10.2 (to depict maps) are used. According to the 20 studied years, only the maps of the 1990, 2000, 2005 and 2011 are displayed.

3. Results and Discussion

Analysis results indicate that Kaya Identity, taking into account major factors influencing on emissions (population, GDP, carbon intensity and energy intensity), can be considered among the powerful models to estimate CO_2 emissions. Despite the ease and simple structure of this equation, it could be considered a good estimator of CO_2 emissions, not only at a global level, but also for many countries at national level.

The decomposition of Kaya Identity, in order to evaluate the role of different factors influencing on CO_2, during 1990-2011 for the world as a whole (215 countries), is shown in Figure 1. Based on this diagram, energy intensity has been decreasing rapidly. In addition, carbon intensity follows a decline path but not as steep as energy intensity done. In contrast, population and GDP per capita have a strong increase rate and as a consequence, CO_2 emission is growing. In sum, more attempts are needed on the path of carbon intensity improvement. Development of renewable energies, rapid switch from dirty fossil fuels to clean ones and setting limitations on coal consumption are robust suggestions for this purpose.

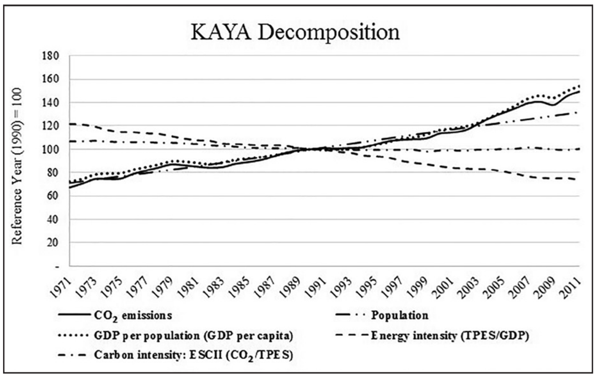

Figure 1. Decomposition of influencing factors on Kaya identity

Another achievement of the present study is the evaluation of the expected CO_2 emissions calculated by Kaya and comparing them with real data during a period of 20-year with one year steps. For a better understanding and summing up, the results of this comparison are shown as global maps only in four time section (including 1990, 2000, 2005 and 2011), presented in Figures 2 to 5. In these figures, the difference of emissions (real - expected) for 1990 to 2011 are categorized.

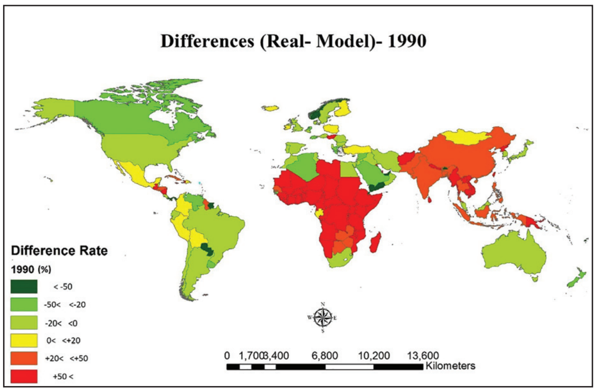

Figure 2. The difference of real and calculated (Kaya) emissions-1990

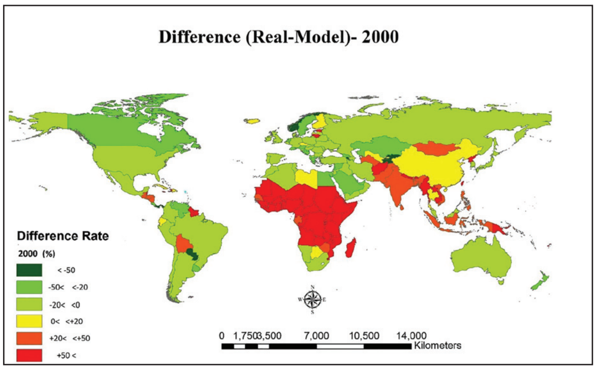

Figure 3. The difference of real and calculated (Kaya) emissions-2000

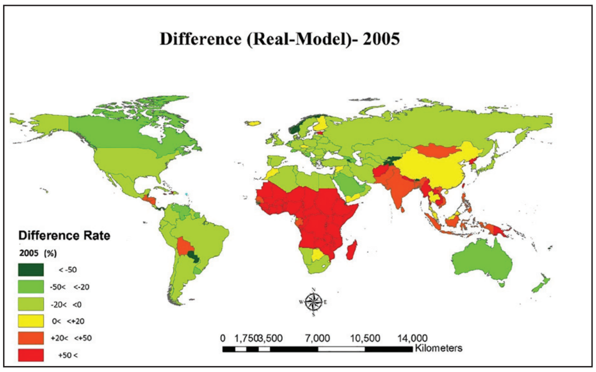

Figure 4. The difference of real and calculated (Kaya) emissions-2005

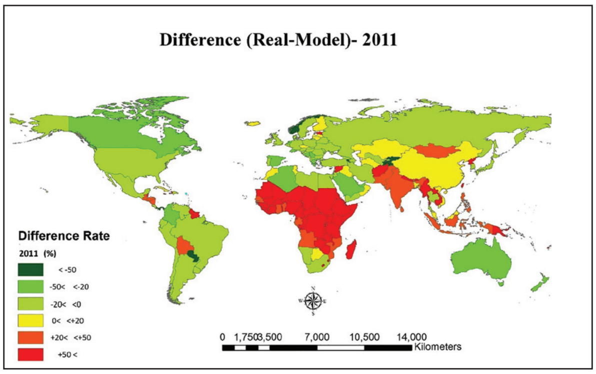

Figure 5. The difference of real and calculated (Kaya) emissions- 2011

Typically, the accuracy estimation of a model can be judged by considering the error values. Models with less than ±20% error are considered accurate and reliable, between 20-50% is acceptable; for higher values, a modification of the model is suggested. Based on this rule of thumb, findings of the present study, from all 251 countries under evaluation, during 1990-2011, are classified into five groups (Table 1). Group 1 includes those with accurate results in comparison with reality (with less than 20% error). Groups 2 to 4 consist of countries with more difference in estimated emissions with real data; and finally small countries or islands with no data availability are placed in group 5. It should be emphasized that despite the large number of countries in group 5, they are accounted for only 1.9% of emissions around the world, which is negligible. Although more than 80% of emissions is related to countries which, according to Kaya Identity are of an acceptable margin of error, are predictable.

Table 1. Statistic of 251 countries estimated by Kaya and compared with real data (1990-2011)

Classification	Difference (%) Real- Kaya	Number of Countries	Population (%)	Share of GDP (%)	Share of Emissions (%)
Group 1	≤ 20	74	54.5	77.4	81.7
Group 2	20 < ≤ 50	27	29.0	12.5	15.7
Group 3	50 < ≤ 100	23	8.5	1.6	0.9
Group 4	more than 100	4	0.3	0.4	0.1
Group 5	no Data	123	8.3	8.4	1.9

The number of countries that Kaya Identity can estimate their emissions close to reality (with less than 20% difference) is increasing and from 56 in 1990 improved to 82 and 71 during next decades. These countries covered about 52% of the total world population in 2011. In addition, about 74% of world›s GDP and more than 80% of CO_2 emissions are related to these countries and are estimated well by Kaya Identity. Table 2 depicts the statistics related to countries that are estimated well (with less than 20% difference) by Kaya and share of population, GDP and CO_2 emission of this group of countries. It could be concluded that the model›s ability to predict emissions has increased over time.

The top emitter countries in 2015 include China, United States, India, Russia, Japan, Germany, Korea, Canada, Iran and Brazil. Another interesting result of the present study is that, except for Canada and India, all the top ten emitter countries are placed in the group of countries which can be estimated accurately by Kaya.

In contrast, five countries (Armenia, Malta, Paraguay, Singapore and Tajikistan) represent a great error in the estimation of emissions by Kaya Identity (more than 100%), so that real emission amounts are far less than the predicted ones. This conclusion is related to the type of economic activities that have been done in a country. For example, agriculture, husbandry, tourism, etc., are effective on the economy of a country or a region but with no direct effect on GHG emissions. Kaya Identity is unable to predict emissions in the other sectors, which are far from fossil fuel consumption and industry. Development of the other models and driving forces with the ability to predict emissions from non-combustion sectors must be put on the agenda.

Table 2. Statistic of countries that follow Kaya identity (with less than 20% difference), Group 1

Year	Number of Countries	Population (%)	Share of GDP (%)	Share of Emissions (%)
1990	56	25	63.8	64.0
2000	57	51.5	75.8	80.6
2005	82	52.2	77.2	82.0
2011	71	52.5	74.3	80.4

Conclusions:

The estimation of the CO_2 emissions and comparing the results with real data among 215 countries for a period of 20 years (1990-2011) are the most important aims of the present study. Based on the amount of errors in the prediction of emissions (%) and data availability, five groups are categorized. It is concluded that this simple estimator can be used for the prediction of future emissions in many countries and may cover about 80% of emissions around the world. In addition, the evaluation of the most important factors influencing on the emission of a country is possible by the decomposition of Kaya influencing factors. For example, during a study done on China (Xiangzhao and Xuechen, 2009), Kaya Identity, in combination with macroeconomic factors, was used for a period of 34 years (1971-2005), indicating that the economic development and population growth are mainly responsible for CO_2 emissions. Based on the results of the present study, during the two past decades, Kaya Identity has worked as a suitable estimator for the prediction of CO_2 emissions of China (with less than 5% error).

Another study applied Kaya Identity as an extended format to identify drivers of CO_2 emissions in the former Soviet Union and among 15 countries (Brizga et al., 2013). It was mentioned that during different stages of economic development (from 1990 to 2010) different factors played different roles on emission rates. The evaluation of this case in the present article revealed that, during this period (1990-2011), Kaya Identity was not followed by all this group. Armenia experienced about -85.6% error between real data and Kaya prediction, Azerbaijan (-21.2%), Belarus (-3.4%), Estonia (+59.1%), Georgia (-36.7%), Kazakhstan (+1.9%), Kyrgyzstan (-94.6%), Latvia (+4.1%), Lithuania (+2.8%), Moldova (-10.2%), Russia (-6.5%), Tajikistan (-145.7%), Turkmenistan (-0.6%), Ukraine (-5.1%) and Uzbekistan (-10.0%) and each country follows a different pattern in emissions.

Decomposition of carbon emissions in the period of 1990-2010 is subject of a study done on Ireland (O'Mahony, 2013). Affluence and population lead to more emissions and are countered by energy intensity and fossil fuel substitution. We found that Ireland›s emission data are in good coordination with Kaya results (with about 12% error).

Economic development, carbon intensity and the change in the composition of the economy are introduced as the most contributors to the rise in CO_2 emissions in Turkey (1980-2003) (Lise, 2006) and we recommend Kaya Identity as a good model for this evaluation (with an average -6.2% error in prediction).

However, the present study can help in giving a better understanding of Kaya Identity for emission prediction. It should be mentioned that, for each country or region, more parameters could be suggested to extend or improve this model. In this way, more accurate predictions may become possible. Governments and policy makers can better analyze the influencing factors, paving the way for achieving more emission reduction.

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