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Quantifying rates and drivers of change in long-term sector- and country-specific trends of carbon dioxide-equivalent greenhouse gas emissions

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ABSTRACT

Significance, direction, rate, and drivers of change in total carbon dioxide -equivalent (CO_2-eq.) greenhouse gas (GHG) (GHG_{CO_2-e}) emission from eight sectors of 41 Annex-I countries were quantified over the period of 1990–2012 using data-driven models. The Mann-Kendall (MK) test for trend analysis indicated an overall downward trend by 10.5% with a Sen's slope of −613 Mt CO_2-eq./year. The highest GHG_{CO_2-e} emission growth and reduction occurred with the sectors of energy, and land use, land use change and forestry (LULUCF) at rates of 1.2 and −1.0 gigatons (Gt) CO_2-eq./year, respectively. Out of the 41 countries, 18 (44%) and 12 (29%) significantly reduced and increased their GHG_{CO_2-e} emission rates, respectively ($p < 0.1$). The best-fit multiple non-linear regression (MNLR) model as a function of population density, gross domestic product per capita, fractional contribution of renewable energy to total energy production, country, and year elucidated 99.8% of variation in total GHG_{CO_2-e} emission and had the predictive power of 99.8% based on leave-one-out cross-validation.

Contents

1. Introduction

Svante Arrhenius (1896) is the first researcher to quantify and to speculate about impacts of the increased atmospheric concentration of carbon dioxide (CO_2) on the greenhouse effect and long-term variations in climate [1]. Charles D. Keeling performed the first continuous CO_2 measurement at 3400 m at Mauna Loa (HI, USA) in 1958 to better understand the relationship between

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CO_2 emitted from the burning of fossil fuels into the atmosphere and air temperature [20]. Since then, significant efforts have been made in the scientific arena to understand how the atmospheric concentrations of not only greenhouse gases (GHGs) including CO_2, water vapor (H_2O), methane (CH_4), ozone (O_3), nitrous oxide (N_2O), hydrofluorocarbon (HFC), chlorofluorocarbon (CFC), and perfluorinated carbon (PFC) but also aerosols influence the earth's energy budget and climate regime [2,8–10,12,17,24,36,40]. Mean global atmospheric CO_2 concentration has increased from the pre-industrial level of 277 ppm (ppm) to around 395 ppm currently, with an increase by 0.74 °C in global average air temperature since the pre-industrial times (1 Gt C=2.12 ppm) [17,26]. Mean annual global estimates between 2004 and 2013were reported as 10.6 ± 2.9 and 9.5 ± 1.8 Gt CO_2 for terrestrial and oceanic sinks and as 32.7 ± 1.5 Gt CO_2 and 3.3 ± 1.8 Gt CO_2 for the human-induced sources of fossil fuel burning and cement production, and land-use change, respectively (1 Gt C=3.67 Gt CO_2) [4,26]. Globally, the total terrestrial and oceanic CO_2 sinks offset 43–69% of the total human-induced CO_2 sources [26].

Global climate change involves changes in air and soil temperature, daytime versus nighttime temperature, growing versus non-growing season temperature, precipitation regime, and extreme weather conditions [33,35,42,45]. These changes in turn have domino effects on snow and ice masses, sea level, timing and duration of seasonal activities of animals and plants, species distribution and abundances, spread of outbreaks and diseases, and socio-economic welfare [7,13–19,27–32]. Towards preventing and mitigating adverse impacts of GHG emissions on the well-being of humans and ecosystems, the Kyoto Protocol was signed internationally by 84 Parties in Kyoto (Japan) on 11 December 1997 so as to be committed to decrease GHG emissions by at least 5% of their 1990 levels over the five-year period (2008–2012), entered into force on 16 February 2005 and has been recently ratified by a total of 192 Parties [25]. Rogelj et al. [37] reported that total GHG emission should be reduced to the range of 41–47 Gt CO_2-equivalent (eq.)/year as the maximum appropriate target by 2020 so as to limit a rise in global average temperature to ≤ 2 °C above the pre-industrial levels called the threshold for the dangerous anthropogenic interference as the United Nations Framework Convention on Climate Change (UNFCCC) Parties agreed.

Our capacity to assist policy institutions and individuals in making better-informed decisions as well as to monitor international climate change cooperation and country-specific performances for any climate stabilization target depends on the development of data- and model-based assessments of the inter-annual variability, trend, and drivers of change. The comparative assessments of GHG emission time-series data provide information about sector- and country-specific dynamic performances towards fulfilling the commitment to the Kyoto Protocol. Therefore, the objective of this study was to detect the significance, direction, rate, and drivers of the observed trends of total CO_2 –eq. GHG (GHG_{CO_2-e}) emission for the eight sectors of the 41 Annex-I countries over 23 years using data-driven models.

2. Material and methods

2.1. Data description

Countries that adopted the Protocol to the UNFCCC are required to report their GHG emission inventories (expressed in megatons, Mt) on an annual basis. The total and sector-specific annual GHG_{CO_2-e} (CO_2, CH_4, N_20, SF_6, PFCs and HFCs) emission data (Mt CO_2-eq./year) for the period of 1990–2012 were used in this study for a total of 41 Annex I countries including Turkey and the following eight sectors: energy, energy industries, industrial processes, land use, land use change and forestry (LULUCF), manufacturing industries and construction (MIC), transportation, wastes, and agriculture and were acquired from the UNFCCC [46,47] (2012). Population density (PD, people per km^2), and gross domestic product (GDP, per capita of USD) data (inflation-adjusted 2010 prices) between 2001 and 2011 were obtained for 31 countries from the World Bank [53], and the USDA-ERS International Macroeconomic Data Set [50], respectively. Similarly, data about contribution of renewable energy to total energy production (RE, %) were obtained from OECD [34].

The principle of measurement, reporting and verification (MRV) was elaborated by a number of decisions by the Conference of the Parties for enhancing mitigation actions against climate change. According to the MRV principle, what are measured, reported and verified occur through biennial update reports (BURs), national communications, international consultation and analysis (ICA), and key assumptions and methodologies associated with the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, and the Greenhouse Gas Inventory Software for non-Annex I Parties (NAIIS) that the UNFCCC secretariat developed which incorporated all the elements prescribed by decision 17/CP.8. The MRV principle involves (1) inventory of GHG emissions by sources and removals by sinks; (2) enhancement of GHG emission reductions and removals by sinks relative to a baseline scenario; and (3) reporting of progress in achievement and implementation of climate change mitigation and adaptation as well as support received/needed in the form of finance, technology and/or capacity-building. Parties make their national GHG inventories following the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories complemented by the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (2000) and the IPCC Good Practice Guidance for LULUCF (2003) and choosing one of the three tiers of the IPCC inventory methodologies according to their data availability: Tier 1 represents the minimum, or default method, while Tiers 2 and 3 involve more elaborate either source category-specific or technology-based methods.

2.2. Direction of trends

The Mann-Kendall (MK) test, a non-parametric statistical test, was used in this study to detect long-term trends in GHG_{CO_2-e} emissions between 1990 and 2012. The MK test is not sensitive to missing values, outliers, and data distribution type [21,30]. The MK "S" statistic can be calculated using Eq. (1) [39]:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{1}$$

where x_j and x_k are annual data values, and $\operatorname{sgn}(x_j - x_k)$ is an indicator function that takes a value of −1, 0 and 1 according to the sign of $(x_j - x_k)$ as presented below in Eq. (2) [51]:

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if} \quad x_j - x_k > 0 \\ 0 & \text{if} \quad x_j - x_k = 0 \\ -1 & \text{if} \quad x_j - x_k < 0 \end{cases} \tag{2}$$

The positive and negative signs of S represent the upward and downward direction of a trend, respectively. The variance of S takes into account tie (repeated) values in the data as presented in Eq. (3) [22]:

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5) \right] \tag{3}$$

where q is the number of tied groups, and t_p is the value in the pth group. The normal test statistic Z is determined using Eq. (4)