Gains in economic energy efficiency as the impetus for increasing atmospheric carbon dioxide

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Abstract. Growth of anthropogenic carbon dioxide (CO_2) emissions is frequently diagnosed as a product of population, per capita economic production, the energy intensity of economic production (or inverse of its energy efficiency), and the carbon intensity of energy. This paper introduces an alternative, prognostic emissions model that accounts for human system feedbacks: economic production adds to a generalized form of infrastructure; infrastructure enables energy consumption through a constant of proportionality; in return, energy consumption powers economic production: CO_2 is emitted as the waste-product. Core assumptions in the model are shown to be supported by economic records from recent decades, implying that, perhaps surprisingly, it is the growing energy efficiency of the economy, not increasing population or standard of living, that most directly explains accelerating CO_2 emisssions. Thus, further increases in energy efficiency are likely to backfire as a mitigation strategy. Instead, any strategy for limiting future atmospheric CO_2 emissions requires strong and accelerating reductions in the carbon content of energy.

1. Introduction

Recent observed increases in atmospheric carbon dioxide (CO_2) concentrations are primarily a response to human activities [1]. Projections of future climate change are sensitive to assumed anthropogenic carbon dioxide emissions from the combustion of fossil-fuels. A wide variety of scenarios have been developed for the 21st century, ranging from "business as usual" to climate change mitigation in which there is implementation of deep emission reductions [2]. Typically, mitigation strategies aim to stabilize atmospheric CO_2 levels below some environmentally acceptable level. The challenge to society has been formulation of a recipe for a "soft landing", in which CO_2 emissions are reduced without harmful reductions to economic growth.

The traditional framework for interpreting the association between atmospheric CO_2 and human activity has come to be known as the Kaya Identity [3], which expands on the simple relationship between carbon dioxide emissions E, the energy consumption rate a, and the quantity of carbon dioxide emitted per energy unit consumed c

$$E = ca \tag{1}$$

Energy consumption is related to economic production P through the energy efficiency of production f,

$$P = fa \tag{2}$$

where P is normally expressed for simplicity of interpretation in fixed year (i.e. inflation-adjusted or "real") currency instead of in current price (or "nominal") currency. Further, the Kaya Identity references CO_2 emissions with respect to human population p. Thus,

$$E = p \times g \times i \times c \tag{3}$$

where g represents the real economic production per person and $i = 1/f$ represents the energy intensity of real economic production. The Kaya Identity is a useful diagnostic tool often used to forecast carbon emissions, given projections for each of its component terms [3].

The components of the Kaya Identity that have been most clearly associated with recent increases in carbon dioxide emissions are past exponential growth in population p and per capita economic production g [2, 3, 4]. However, climate change mitigation strategies focused on limiting population or standards of living tend to be politically unpalatable, so considerable effort has been directed at technological solutions, aimed either at increasing energy efficiency f (decreasing i) or shifting to energy resources that emit less carbon dioxide (decreasing c) [2, 5, 6, 7].

This report introduces and tests an alternative model for interpreting CO_2 emissions that is prognostic and a function only of f and c. In this model, and in contrast to the Kaya Identity, p and g are relevant but implicit. The model is shown to imply that it is not population or increasing standard of living, but increasing energy efficiency f that most directly accounts for the current rise in CO_2 emissions.

2. A growth model for the economy and emissions

Traditional economic growth models [8, 9, 10, 11] discriminate between capital and labor, and represent the investment in capital as a fractional contribution from production (a "savings"). To illustrate, the Solow Growth Model [9], treats economic growth P as a function of changes in some representation of technological progress A, economic capital K, and human labor L

$$\frac{d\ln P}{dt} = \frac{d\ln A}{dt} + w_K\frac{d\ln K}{dt} + w_L\frac{d\ln L}{dt} \tag{4}$$

where $w_k = d\ln P/d\ln K$, $w_L = d\ln P/d\ln L$, and $w_k + w_L = 1$. Effectively, $1/w_k$ is the inverse of the fraction of production that is saved for capital, and w_L the remainder that is produced by labor.

Here, based on intuitive arguments, an alternative, albeit mathematically similar growth model is introduced. The model relies on two hypotheses. The first is that the rate of economic energy consumption is related to the size of human civilization or economic "infrastructure" I. As defined, infrastructure represents a generalized form of economic capital K that includes all societal elements that facilitate the consumption of energy for the purpose of powering economic production. Infrastructure elements might be non-human, such as working animals, roads, computers and communications; others might be human, including the production capacity of active bodies and brains, more traditionally represented as labor L. Human and non-human infrastructure elements are treated as being functionally indistinct. What is relevant is only that total infrastructure I works to enable the consumption of energy at rate a

$$a = \lambda I \tag{5}$$

where λ is a time-independent constant value. Effectively, infrastructure is a monetary representation of the capacity of civilization to create economically available physical power. Thus, from Eqs. 2 and 5, infrastructure powers economic production through

$$P = \lambda f I \tag{6}$$

Of course, for energy to be consumed, infrastructure must itself be produced. The second hypothesis introduced here is that, because infrastructure powers economic production, economic production is valued in proportion to its capacity to contribute to the development and maintenance of infrastructure. In other words:

$$\frac{dI}{dt} = P \tag{7}$$

Effectively, all real production is an investment in generalized capital. An obvious example of how economic production contributes to I is through the construction of coal mines and power plants. A less obvious example, but one that is functionally equivalent, is the entertainment sector. Entertainment related activities maintain and contribute to infrastructure by facilitating the human desire and capacity to do economic work.

Thus, Eqs. 6 and 7 describe an economic system representing a feedback loop between infrastructure and economic production: economic infrastructure facilitates economic production, which in turn adds to infrastructure. Combined, Eqs. 1, 5 and 7 imply that CO_2 emissions can be represented by

$$E = \lambda c I = \lambda c \int_0^t P\left(t'\right) dt' \tag{8}$$

where the prognostic solution for growth in I is:

$$\frac{d\ln I}{dt} = \lambda f \tag{9}$$

and the the prognostic form for E is

$$\frac{d\ln E}{dt} = \lambda f + \frac{d\ln c}{dt} \tag{10}$$

Prognostic equations can also be supplied for economic production P and energy consumption a by substituting I with the simple algebraic relationships given by Eqs. 5 and 6:

$$\frac{d\ln a}{dt} = \lambda f \tag{11}$$

$$\frac{d\ln P}{dt} = \lambda f + \frac{d\ln f}{dt} \tag{12}$$

Thus, a simple statement is made that, through infrastructure, it is the efficiency of economic energy consumption f that controls the rate of growth of civilization and its waste-products. Note that, there are similarities between Eq. 12 and Eq. 4, insofar that technological progress is incorporated, although referenced more explicitly here with respect to energy. However, unlike Eq. 4, no reference is made to labor.

3. Evaluation

The economic model introduced above is now tested with historical estimates of P, a, and E. For simplicity and relevance these quantities are examined at a global level rather than for nations or regions. The reason for this is that, through atmospheric mixing, carbon dioxide concentrations are nearly equivalent in all locations. Also, through trading in international markets, the valuation of a given economic unit of currency is identical. Thus, only a closed system is examined, in which case details in mixing and trade are implicit.

The validity of the revised Kaya Identity given by Eq. 8, and the growth solution represented by Eq. 9, rests on whether the hypothetical relations given by Eqs. 5 and 7 are observationally supported. Specifically, what must be tested is whether there exists a constant coefficient λ that relates the consumption of energy a to infrastructure I (Eq. 5), where infrastructure is the accumulation of real economic production over history (Eq. 7):

$$\lambda\left(t\right) = \frac{a\left(t\right)}{I\left(t\right)} = \frac{a\left(t\right)}{\int_0^t P\left(t'\right)dt'} = const. \tag{13}$$

For the years 1970 to 2004, records are available for both global energy production [12] (it is assumed that production and consumption rates are, at least on average, equivalent) and economic production [13]. There are no explicit records for global infrastructure worth I, and, strictly speaking, calculation of I would require yearly records of global economic production P starting from the beginning of civilization. Because such records are not available, what is used instead is a combination of recent annual records, and more sporadic estimates from over the past two millenia [14]. Estimates of P in 1990 market exchange rate dollars are available for the years since 1970 [13]. Intermittent, long-term historical estimates are available in Geary Khamis purchasing power parity (PPP) 1990 US dollars for the years 0 to 1992 [14].

In general, the motivation for expressing valuation in PPP instead of exchange rate dollars is to account for disparities in product valuation that exist between countries. In PPP dollars, product valuation is equalized according to its apparent contribution to standard of living. Countries with a low standard of living tend to have a relatively high gross domestic product when expressed in PPP rather than market exchange rate dollars. Because the focus of this study is energy production and associated CO_2 emissions, rather than national standard of living, historical records of market exchange rate valuations are preferred. Exchange rate P is assumed to most accurately reflect the total energy costs associated with manifesting products and services in the respective nations where they are consumed.

To account for any discrepancy between PPP and exchange rate estimates in historical records for P, market exchange rate data from 1970 onwards is used to devise a time-dependent correction factor π to be applied to PPP records such that $\pi = \mathrm{PPP}/\mathrm{exchange\,rate}$ (Fig. 1). For the period 1970 to 1992 where both PPP and market exchange rate estimates of P are available, the fitted value for π is $\pi = 1 + 0.258\exp\left[(t-1998)\right]/73$. This correction factor is extrapolated and applied to all PPP data between the years 0 and 1969. From 1970 onwards, the measured exchange rate values are used. Because the historical estimates of P in PPP dollars are increasingly sparse with distance back in time (there are only three data points for the period 0 to 1500), the corrected dataset for P is mapped to a yearly distribution using a cubic spline fit. The corresponding estimates of infrastructure I represent the yearly accumulation in P (Fig. 1), i.e. $I(t) = \int_0^t P(t')\,dt'$.

Fig. 2 shows that, between 1970 and 2004, infrastructure value and energy production both approximately doubled, and that $\lambda(t)$ maintained a relatively constant value of 0.344 ± 0.013 exajoules per trillion 1990 US dollars per year, or equivalently, the value of a 1990 dollar was supported by 10.4 ± 0.4 mW of continuous energy consumption. The deviations in $\lambda(t)$ are sufficiently small (~3 %) that they plausibly reflect uncertainties in historical estimates of I and a. It may be inferred that λ is at least functionally constant.

The implication of λ being constant is that Eqs. 8 and 9, which define the proposed growth model, are valid. Accordingly, Eqs. 10 and 12 can be applied to forecast trajectories in economic production and carbon dioxide emissions growth based only on known or hypothetical trajectories for f and c.

For the sake of illustration, numerical simulations are set up as an initial value problem, in which I, P, and E are initialized to conditions observed in 1970, and λ is assumed to be 0.344 exajoules per trillion dollars per year (Fig. 2). If Eqs 10 and 12 were fully prognostic, they would include a model for $d\ln f/dt$ and $d\ln c/dt$, the rates of change in economic energy efficiency (or the innovation rate) and CO_2 emission intensity of energy (or the carbonization rate). While this type of forecasting is a topic of contemporary research [3, 10], it is beyond the scope of this study. Instead, average values are supplied for the respective growth rates of these two parameters based on observations of f and c from the period 1970 to 2004, as shown in Fig. 3. Here, the CO_2 emission intensity of energy c is modified from its standard representation to represent the increase in atmospheric concentrations of CO_2 that would be expected in a well-mixed atmosphere in the absence of terrestrial sink and source terms (1 ppmv CO_2 = 2.13 Gt emitted carbon [15]). While there is substantial variability in innovation and carbonization rates over this period, the average value of $d\ln f/dt$ is 0.95% yr^{-1}, and the average value of $d\ln c/dt$ is -0.3% yr^{-1}. If these rates are provided as model input, Eqs. 10 and 12 produce a faithful reproduction of the observed average growth rates in economic production (2.8% yr^{-1}) and carbon dioxide emissions (1.5% yr^{-1}) (Fig. 4).

4. Discussion

To elaborate, the equation for CO_2 emissions E presented here (Eq. 8) displays several important differences from the Kaya Identity (Eq. 3). First, the Kaya identity treats population p as the driving force behind CO_2 emissions. Here, it is argued that it is infrastructure that drives emissions; growth in population, or labor, may be implicit to emissions growth, but only insofar as they are part of total infrastructure: as a vehicle for facilitating economic energy consumption, economic production, and CO_2 emissions, people have no intrinsic distinction from, say, bridges or roads.

Second, the Kaya identity treats changes in population p, per capita production g, and technology $i = 1/f$ as parameters that act independently [5]. Here, a growth model is provided in which the rate of change in economic energy efficiency $d\ln f/dt$ (or innovation rate) determines the growth rate of humanity's production $P = pg$ through a simple feedback loop (Eq. 12). In fact, if the innovation rate is positive, there is an exponential increase in the efficiency of economic production λf with characteristic time-scale $\tau_f = 1/\left(d\ln f/dt\right)$, and, from Eq. 9, infrastructure increases super-exponentially (Fig. 1). For the same reasons, if carbonization of the energy supply c is assumed to be constant in Eq. 10, the growth of CO_2 emissions E is also super-exponential. Thus, starting at some time $t = 0$

$$\frac{I}{I\left(0\right)} = \frac{E}{E\left(0\right)} = \exp\left[\lambda f\left(0\right)\tau_f\left(e^{t/\tau_f} - 1\right)\right] \tag{14}$$

Note that growth condenses to the single exponential form in the limit of $t \ll \tau_f$. There has been a lack of clear recent evidence for super- or sub- exponentiality in recent emissions growth, but this can be explained if it is considered that the time-scales for innovation τ_f and decarbonization $\tau_c = -1/\left(d\ln c/dt\right)$ have been long – approximately 100 years and 300 years respectively (Fig. 3).

From the perspective of time-series analysis, the frequency spectrum for economic energy efficiency λf is "reddened": it varies much more slowly than the innovation rate $d\ln f/dt$ because it reflects the integrated history of innovation. Inflation-adjusted innovation can be quite variable, due, for example, to wars or natural disasters, which require that innovation be directed at maintaining rather than improving infrastructure. So, on short time-scales, and as seen in Fig. 3, innovation might be either positive or negative. This allows the rate of economic production to either grow or shrink (Eq. 12). On the other hand, if averaged over longer time-scales dln f/dt is positive, the growth of production and energy consumption accelerates (Eq. 11).

That increasing energy efficiency tends to lead to more rather than less energy consumption was first noted in the 19th century by William Stanley Jevons [16], who observed that the introduction of more efficient steam engines led to increased demand for coal. The conclusion has been echoed in more recent numerical and observational studies of national economies [17, 18, 19], but without satisfactory explanation, perhaps because such studies included the complicating factor of labor as an important component of their analyses. As it has been shown here, if labor is treated implicitly as a component of infrastructure, and infrastructure is tied to energy consumption, "Jevons' Paradox" is simply summarized by Eq. 11.

While energy consumption is intrinsically linked to economic production and infrastructure, it is at least theoretically possible to decouple economic growth from growth in carbon dioxide emissions. What is required is that, from Eqs. 10 and 12, $d\ln E/d\ln P = 0$, in which case,

$$\frac{-d\ln c/dt}{\lambda f} = 1 \tag{15}$$

Economic efficiency λf is currently running at approximately 2.3% per year, and decarbonization $-d\ln c/dt$ between 1970 and 2004 was approximately 0.3% per year. Decoupling requires then that decarbonization of the economy be accelerated by about a factor of 8. To put this in perspective, such decoupling would require the annual provision globally of approximately 300 GW of new non-carbon emitting power capacity, or a complete moratorium on new capacity to consume fossil fuels (Eq. 11). Moreover, because $d\ln f/dt$ is currently positive, decoupling requires rates of decarbonization that increase correspondingly.

5. Conclusions

This paper has introduced a model for describing the growth of global economic production and carbon dioxide emission that is both theoretically simple and observationally supported. The model implies that, as a strategy for mitigating climate change, increasing energy efficiency should be expected to backfire. Higher efficiency may enable higher production per unit energy in the moment, but with the consequence of higher capacity of infrastructure to facilitate energy consumption in the future. If the energy supply remains fossil based, CO_2 emissions will increase accordingly. For economic production P to continue to rise without such an associated increase in CO_2 emissions, what is required is rapid and accelerating decarbonization of the world economy, achievable through a firm cap on fossil-fuel consumption capacity.

It seems noteworthy that similar energy-based feedback arguments have been used to explain the evolution of species [20]. In this case, organic behavior might also be ascribed to the human system. Civilization employs innovation to capitalize on available energy resources for the purpose of promoting growth. This leads to greater future energy consumption, and, as with many other biological systems, increasing production of CO_2.

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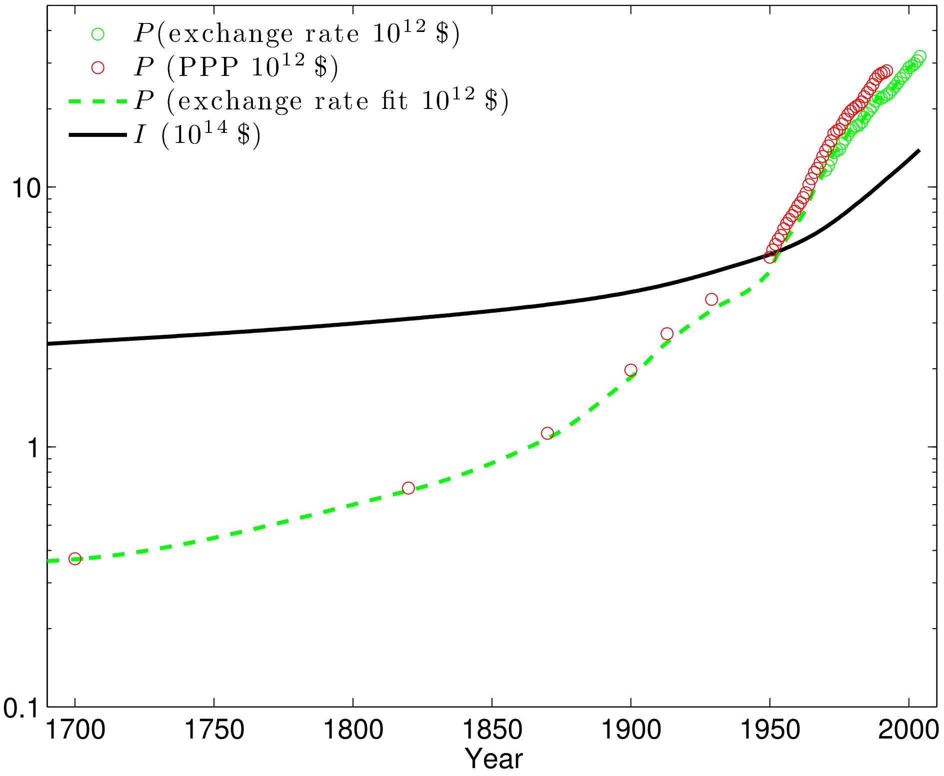

Figure 1. Estimates of gross world product P in exchange rate, and purchasing power parity (PPP) 1990 U.S. dollars, with a fitted exchange rate value derived for years 1970 back to 0. Infrastructure I represents the accumulated value of market exchange rate P.

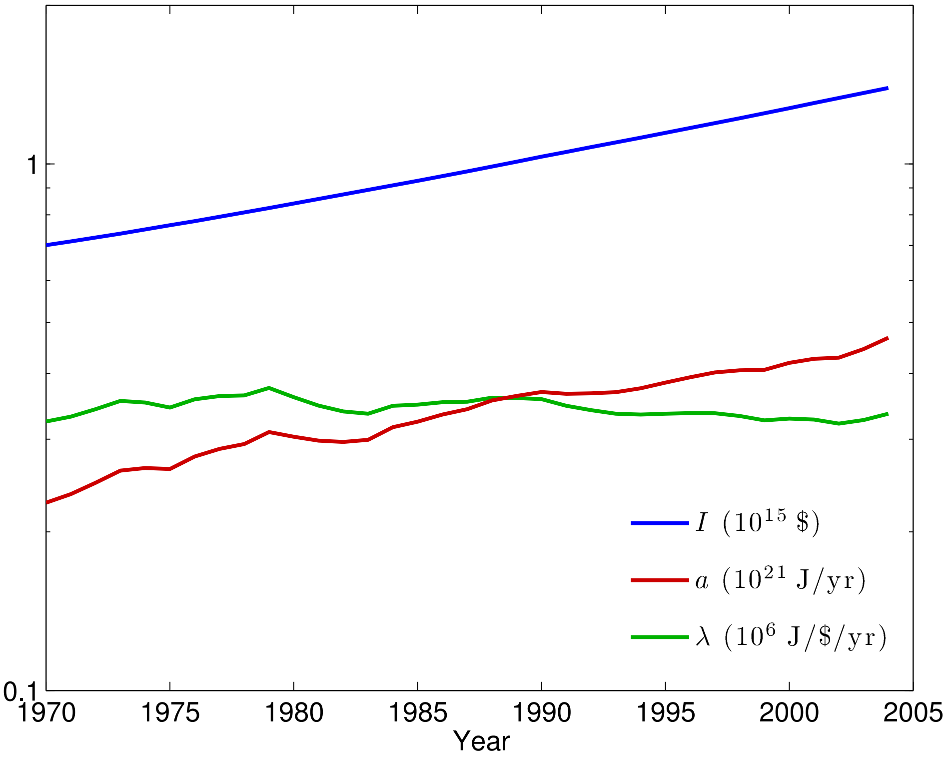

Figure 2. Trajectories for total infrastructure I and total energy production a during the period 1970 to 2004. The parameter λ represents the ratio a/I.

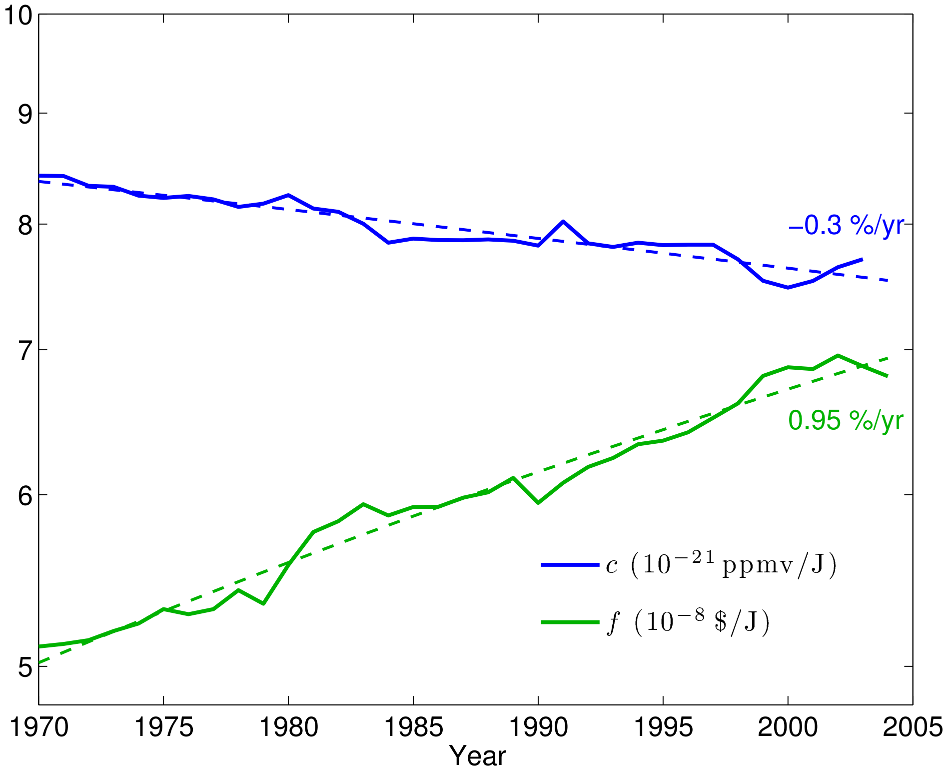

Figure 3. Trajectories for real economic energy efficiency f and the carbon dioxide emission intensity of energy c, for the period 1970 to 2004. Dashed lines represent a least-squares first-order fit.

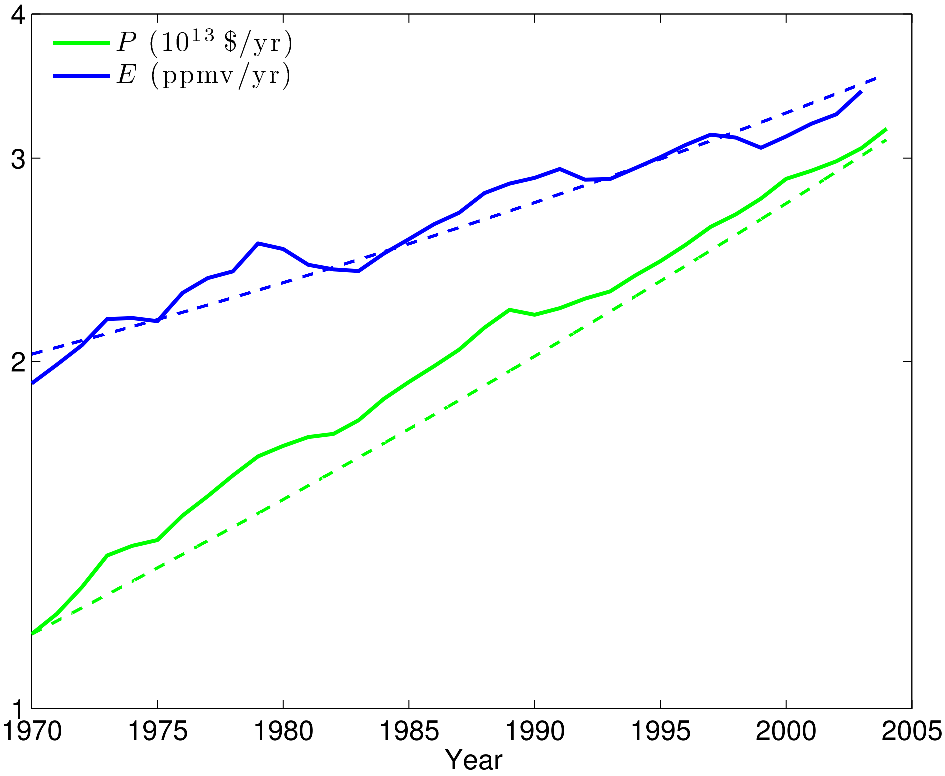

Figure 4. Observed (solid) and simulated (dashed) trajectories in real global world production P and carbon dioxide emissions E between 1970 and 2004.