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# No way out? The double-bind in seeking global prosperity along with mitigated climate change

**T. J. Garrett**

Department of Atmospheric Sciences, University of Utah, Salt Lake City, Utah, USA

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Correspondence to: T. J. Garrett (tim.garrett@utah.edu)

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## Abstract

In a prior study (Garrett, 2011), I introduced a simple thermodynamics-based economic growth model. By treating civilization as a whole, it was found that the global economy's current rate of energy consumption can be tied through a constant to its current accumulation of wealth. The value of the constant is $\lambda = 9.7 \pm 0.3$ milliwatts per 1990 US dollar. Here, this model is coupled to a linear formulation for the evolution of atmospheric $CO_2$ concentrations. Despite the model's extreme simplicity, multi-decadal hindcasts of trajectories in gross world product (GWP) and $CO_2$ agree closely with recent observations. Extending the model to the future, the model implies that the well-known IPCC SRES scenarios substantially underestimate how much $CO_2$ levels will rise for a given level of future economic prosperity. Instead, what is shown is that, like a long-term natural disaster, future greenhouse warming should be expected to retard the real growth of wealth through inflationary pressures. Because wealth is tied to rates of energy consumption through the constant $\lambda$, it follows that dangerous climate change should be a negative feedback on $CO_2$ emission rates, and therefore the ultimate extent of greenhouse warming. Nonetheless, if atmospheric $CO_2$ concentrations are to remain below a "dangerous" level of 450 ppmv (Hansen et al., 2007), there will have to be some combination of an unrealistically rapid rate of energy decarbonization and a near immediate collapse of civilization wealth. Effectively, civilization is in a double-bind. If civilization does not collapse quickly this century, then $CO_2$ levels will likely end up exceeding 1000 ppmv; but, if $CO_2$ levels rise by this much, then the danger is that civilization will gradually tend towards collapse.

## 1 Introduction

Despite decades of public awareness of the potential for fossil fuel consumption to lead to dangerous climate change, anthropogenic emissions of $CO_2$ have accelerated (Canadell et al., 2007; Raupach et al., 2007). The implications of civilization continuing





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on this path are environmental changes that are both irreversible and profound, including amplified hydrological extremes, storm intensification, sea level rise, and extreme mammalian heat stress (Hansen et al., 2007; Allan and Soden, 2008; Solomon et al., 2009; Vermeer and Rahmstorf, 2009; Sherwood and Huber, 2010).

The response of natural systems to elevated $CO_2$ levels can be quantified in sophisticated Earth System Models or EaSM's (Gent and Co-authors, 2009). Assessing the impacts of climate warming on society is just as challenging. Typically the approach is to couple a system of economic equations to a medium complexity climate model. Normally, these Integrated Assessment Models (IAMs) make regionally-based assessments of the economics of production, investment, consumption, welfare, discount rates, population and rates of technological change. These economic functions are coupled to functions for atmospheric temperature and climate damage. From within a parameter space that might be of order 100 variables, the model outcome is a long-term optimized trajectory for long-term societal welfare. This optimal trajectory serves as the reference point to which future policy measures (for example the Copenhagen Accord) can be compared (Nordhaus and Boyer, 2000; Keller et al., 2004; Nordhaus, 2010). Uncertainty in the optimal path, when addressed, is modeled using Monte Carlo simulations within a portion of the total parameter space (Mastrandrea and Schneider, 2004).

Modern IAMs are based on neo-classical economic models that, unlike EaSMs, do not explicitly represent physical flows. Here, a different approach is taken, which is to make a comprehensive appeal to thermodynamic laws in order to make deterministic forecasts of the coupled evolution of the global economy and greenhouse warming. Civilization is as much a part of the universe as is the atmosphere. Therefore, the intent of this article is not to focus on evaluation of the merits of any potential policy actions. Rather, the aim is provide a range of physically constrained trajectories for how we might expect the atmospheric composition and the global economy to evolve over the coming century.





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## 2 A physics-based economic framework

In an earlier article (Garrett, 2011), I introduced an economic growth model that treated civilization from a thermodynamic standpoint illustrated in Fig. 1. In this conception, civilization lies along a surface where, on average, all material is in local thermodynamic equilibrium and has the same potential energy. Expressed another way, civilization is approximated as a surface with constant temperature and pressure, or constant specific entropy. From this perspective, no distinction can be made between the internal components of civilization. Unlike traditional economic models, there is no explicit account for households, firms, governments or banks, nor the flows to and from these components. Rather, civilization is considered only as a whole. It is defined at a sufficiently low resolution that the only resolved distinction is between civilization and known primary energy reservoirs (e.g. coal, oil, uranium, etc.).

Here, energy reservoirs lie along a higher potential surface than civilization. The interface that separates these two surfaces is defined by a gradient in potential energy $\Delta G$ that drives material flow downward to redistribute the balance of potential energy towards the lower potential surface. This flow of energy from high to low potential is a "heating" of civilization that is equivalent to the rate $a$ at which civilization consumes the potential energy in primary energy resources.

Defining the size of the potential gradient to be linearly proportional to the flow rate of potential energy across it, then

$$a = \alpha \, \Delta G \qquad (1)$$

where, $\alpha$ is a constant rate coefficient. The flow of material down the gradient towards civilization adds to civilization's material bulk. The increase in civilization bulk "stretches" the length of the gradient. Effectively, heating $a$ enables growth of the interface. The convergence of material in civilization can be termed work $w$ because it will expand the material interface at rate

$$\frac{d\Delta G}{dt} = w = \epsilon a \qquad (2)$$





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Here, $\epsilon = w/a$ is the efficiency of the conversion of heating to doing work. Unlike the normal conception of work, which is done to raise the potential of some outside agency, here work is done by civilization to increase the potential of civilization itself.

Figure 1 shows that if the material interface grows, then civilization expands into previously inaccessible reservoirs of potential energy. This expansion creates a positive feedback loop that results in exponential growth (or decay) in the rate of primary energy consumption $a$. Combining Eqs. (1) and (2),

$$\frac{da}{dt} = \alpha \frac{d\Delta G}{dt} = \alpha w = \alpha \epsilon a \equiv \eta a \tag{3}$$

where $\eta \equiv \epsilon \alpha$ is a "rate of return" representing the instantaneous rate of civilization growth or decay[1].

$$a = a_0 \exp{(\eta t)} \tag{4}$$

Note that $\eta$ itself can evolve, so that in the special case where $\eta$ increases with time then $a$ grows super-exponentially. Thus, contrary to what is most commonly believed, increases in energy efficiency $\epsilon$ lead to a higher rate of return $\eta$ and accelerated growth of the consumption of primary energy supplies $a$, something known variously as "backfire" or "Jevons' Paradox" (Saunders, 2000; Alcott, 2005; Sorrell, 2007; Owen, 2010). An efficient system grows faster and consumes more. Note that, Eq. (4) also provides for exponential decay, provided that net work is done on civilization by the environment rather than the reverse. In this case, the interface represented in Fig. 1 shrinks, and $w$, $\epsilon$ and $\eta$ are negative.

[1]Strictly, $\Delta G = \breve{n}\Delta\mu$ where $\breve{n}$ is the material length of the interface defined by a potential difference per material unit $\Delta\mu$. Also, the flow of energy $a = (dn/dt)\Delta\mu$ is the flow of material across the gradient at rate $dn/dt$. Thus, since $a = \alpha\Delta G$, $\alpha = 1/\breve{n}(dn/dt)$ is effectively a diffusivity constant. Also, the stretching $w = d\Delta G/dt = \Delta\mu d\breve{n}/dt$ represents a material addition to the material interface $\breve{n}$ rather than to the potential difference $\Delta\mu$ (which is assumed to be fixed). Thus, the rate of return is given by $\eta = d\ln\breve{n}/dt$. See details in Garrett (2011).





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The analogy might be to a growing child, who uses the material nutrients and potential energy in food to produce waste but also to grow. As the child grows, it eats more food, accelerating its growth until it reaches adulthood and growth stabilizes (in which case $\eta \simeq 0$). A healthy, energy efficient child will grow faster than one who is sick and inefficient. A diseased child may even die (in which case $\eta < 0$).

An alternative analogy might be to a growing cloud droplet (Pruppacher and Klett, 1997). A droplet increases its volume through the diffusion of water vapor down a gradient in vapor pressure or, alternatively, potential energy. The diffusion rate is determined by the magnitude of the vapor gradient, but also by the size of the droplet. As the droplet grows, so does the interface between the droplet surface and the vapor gradient. This interface growth introduces a positive feedback that accelerates the rate of vapor flow to the droplet. Assuming the vapor supply is not depleted, there is exponential growth of droplet mass.

In Garrett (2011), this physical perspective was used to describe global economic growth. From a thermodynamic perspective, the global economy is part of the universe, so everything in civilization that happens must be sustained by the downward flow of raw materials along a gradient in potential energy. It seems natural then to suppose that these thermodynamic flows might be expressed fiscally. If so, then a hypothesis can be proposed that the rate of material transfer from high to low potential energy in civilization might be represented by civilization's real, or inflation-adjusted economic value. Expressed mathematically

$$a \equiv \lambda C \tag{5}$$

where, in this case, $a$ is the rate of consumption of the potential energy in primary energy resources (units energy per time), which is related through a constant parameter $\lambda$ to a fiscal representation of global economic wealth $C$ (units inflation-adjusted currency).

Here, it is assumed that wealth $C$ is simply the historical accumulation of gross world economic real production $P$ (units inflation-adjusted currency per time). Real



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production $P$ is an instantaneous quantity that is related to the familiar gross world product (GWP) through

$$\mathrm{GWP} = P\Delta t \tag{6}$$

where, for the sake of economic statistics, $\Delta t$ is normally equal to one year. Total economic wealth is distinct from production in that it is not a differential but an integral quantity (units inflation-adjusted currency). As wealth is defined here, it is represented by the historical accumulation of production

$$C \equiv \int_0^t P\left(t'\right) dt' \simeq \sum_i \mathrm{GWP}\left(i\right) \tag{7}$$

where $i$ is an index covering the full historical record for GWP.

Wealth $C$ is analogous to "capital" in traditional economic growth frameworks in the sense that it has units of currency, rather than currency per unit time. However, it is much more general. Traditional economic models separate capital from labor as distinct motive forces of economic production (Solow, 1956). Further, capital grows only due to "investments" that are separated from household "consumption". Household consumption never adds to capital because people are not normally considered to be part of capital.

Here, the economic approach is quite different. As shown in Fig. 1, civilization is defined as a whole such that no distinction is made between the human and non-human elements of the global economic system. Economic elements are not independent, and none represent some inert stock. Rather, all economic elements in civilization work in concert to enable the "downhill" flows of material in a field of potential energy (for a full discussion see Appendix B in Garrett, 2011). Effectively, civilization is assumed to be homogeneous and "well-mixed". Strictly, this assumption requires only that the speed of financial interactions between all civilization elements is rapid compared to the timescales of global economic growth.





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While the above perspective is highly unorthodox from traditional economic standpoints, it does however rest on a testable hypothesis, which is that $\lambda$ is a constant. The combination of Eqs. (5) and (7) leads to:

$$\lambda \equiv \frac{a(t)}{\int_0^t P(t')\,dt'} \simeq \frac{a\ (t)}{\sum_i \mathrm{GWP}\ (i)} \tag{8}$$

To evaluate the validity of a hypothetical constancy of $\lambda$ in Eq. (8), in Garrett (2011) I employed statistics for world GWP spanning more than 2000 years (Maddison, 2003; UNs, 2010) to calculate wealth $C$ from Eq. (7). Values of $C$ were compared to nearly four decades of statistics for energy consumption rates $a$ (AER, 2009).

As illustrated in Table 1, this comparison supports the hypothesis that the value of $\lambda$, as defined by Eq. (8), is indeed a constant that is independent of time: energy consumption rates $a$ and wealth $C = \int_0^t P dt'$ both approximately doubled in tandem between 1970 and 2008. On a millennial scale, this time interval is short, but it covers a tripling of GWP and more than half of total civilization growth. The full yearly time series indicates that, during this period, $\lambda$ maintained a mean value, with associated uncertainty in the mean, of $9.7 \pm 0.3$ milliwatts per 1990 US dollar (Garrett, 2011). As hypothesized, it indeed appears that $\lambda$ is a constant.

This combination of theoretical and observational support is the key result that serves as a basis for assuming that civilization is financially well-mixed and that wealth is derived most fundamentally from a capacity to enable a flow of potential energy. If it is generally correct, it enables an enormous simplification of what is required to accurately model the global economy and its waste products. At least at a global scale, a sophisticated IAM approach that explicitly considers people and their lifestyles is not necessary in order to forecast future rates of energy consumption. People do not need to be thermodynamically resolved in order to calculate global scale flows.

Taking $\lambda$ to be a constant, it follows from Eqs. (1), (3) and (5) that the “rate of return” for economic growth applies equally to wealth $C$, energy consumption rates $a$ and the size of the interface driving flows $\Delta G$:

$$\frac{d\ \ln \Delta G}{dt} = \frac{d\ \ln a}{dt} = \frac{d\ \ln C}{dt} = \eta \quad (9)$$

Thus, from Eqs. (3), (7) and (9)

$$P \equiv \frac{dC}{dt} = \eta C = \frac{1}{\lambda}\frac{da}{dt} \quad (10)$$

or expressed thermodynamically

$$P = \frac{1}{\lambda}\frac{da}{dt} = \frac{\alpha}{\lambda}w \quad (11)$$

Effectively, economic production $P$ is a fiscal representation of the growth rate of energy consumption *da/dt* by way of doing net thermodynamic work $w$. Combining Eqs. (7) and (11), global wealth arises from the accumulation of net work over time:

$$C \equiv \frac{1}{\lambda}\int_0^t \frac{da}{dt}(t')\, dt' = \frac{\alpha}{\lambda}\int_0^t w\,(t')\, dt' \quad (12)$$

Finally, taking the time derivative of Eq. (10) a second time, the GWP growth rate is given by

$$\frac{d\ \ln P}{dt} = \eta + \frac{d\ \ln \eta}{dt} \quad (13)$$

Thus, what we normally term "economic growth" (i.e. $d\ln P/dt$) is a consequence of an *acceleration* in the growth rate of the rate of energy consumption (i.e. $d^2a/dt^2$).

With respect to emissions of $CO_2$, just as civilization can be treated as being well-mixed over timescales relevant to economic growth, atmospheric concentrations of $CO_2$ are also well-mixed over timescales relevant to global warming forecasts. Thus, for the purpose of relating civilization to atmospheric $CO_2$ concentrations, what matters is only how fast civilization as a whole is emitting $CO_2$. $CO_2$ emission rates are



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determined primarily by rates of energy consumption $a$, but also by the carbonization $c$, defined by

$$c \equiv \frac{E}{a} \tag{14}$$

where, $E$ and $a$ are measured quantities. For convenience, here it is assumed that the $CO_2$ emissions are instantly diluted in the total atmospheric mass (Trenberth, 1981) such that 1 ppmv $CO_2$ = 2.13 Pg emitted carbon. Thus $c$ is expressed in units of ppmv atmospheric $CO_2$ emitted by civilization per Joule of energy consumption. It follows from Eq. (5) that wealth $C$ and $CO_2$ emissions $E$ are fundamentally coupled through

$$E = \lambda c C \tag{15}$$

Drawing from statistics for $CO_2$ emissions from the Carbon Dioxide Information Analysis Center (Marland et al., 2007), Table 1 shows that, like $a$ and $C$, $CO_2$ emissions $E$ have approximately doubled between 1970 and 2008. Meanwhile, the value $\lambda c = E/C$ has stayed approximately constant. Its mean value (and uncertainty in the mean) taken from the entire yearly time series is $2.42 \pm 0.02$ ppmv $CO_2$ per year, per thousand trillion 1990 US dollars of global wealth.

Note that, unlike $\lambda$, the carbonization $c$ is not a fundamental property of the economic system within this framework. At least in principle, it could be more variable in the future than it has in the recent past. Combining Eqs. (9) and (15), emission rates grow at rate that is determined by the growth rate of wealth and the rate of change of carbonization

$$\frac{d\ln E}{dt} = \frac{d\ln C}{dt} + \frac{d\ln c}{dt} = \eta + \frac{d\ln c}{dt} \tag{16}$$

Thus, if decarbonization is as rapid as rate of growth of wealth $\eta$, then emission rates $E$ are stabilized. However, if carbonization $c$ continues to stay approximately constant, then $CO_2$ emissions rates $E$ will remain fundamentally linked to global economic wealth $C$. The implication is that, absent decarbonizing civilization, it is only through economic collapse that $CO_2$ emissions rates will decline.



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## 3 Environmentally driven economic decay

Ultimately, what we would like to know is the future effects of $CO_2$ emissions on the production of global wealth. The IPCC Working Group II (IPCC, 2007b) has identified potential societal damages due to changes in "extremes", notably droughts and floods, and "means", most notably sea-level rise. These will exert a negative feedback on civilization wealth such that, at some point, wealth and atmospheric $CO_2$ become intrinsically coupled: a reduction in wealth due to elevated $CO_2$ concentrations should correspond to lower $CO_2$ emission rates.

### 3.1 Economic accounting of decay

What is shown now is how this environmentally driven economic decay can be expected to manifest itself economically as an inflationary pressure. The inflation rate is normally defined as the year-on-year increase in prices of a given basket of goods. Effectively the value of currency becomes devalued by some inflationary fraction $i$ such that the "real", inflation-adjusted GWP is less than its "nominal" value by some fraction

$$i = \frac{\text{nominal} - \text{real}}{\text{nominal}} = \frac{\widehat{\text{GWP}} - \text{GWP}}{\widehat{\text{GWP}}} \tag{17}$$

There are a wide variety of traditional economic explanations for inflationary forces (Parkin, 2008), with a recognition of there being a balance between the availability of natural resources and the monetary supply. For example, it was concluded by Bernanke et al. (1997) that "... the majority of the impact of an oil price shock on the real economy is attributable to the central bank's response to the inflationary pressures engendered by the shock."

However, here, banks are not explicitly resolved, so no direct account can be made of changes in monetary supply. What can be done, however, is to provide a thermodynamic formulation for how changes in natural resource availability or adverse climatic





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conditions might lead to inflationary pressures. Modeling a central bank's response to these pressures is beyond the scope of this treatment.

Real, inflation-adjusted wealth has been defined here by $C = \int_0^t P\,dt'$ (Eq. 5) or equivalently, the instantaneous function $dC/dt \equiv P$ (Eq. 10), where $P$ is the inflation-adjusted production. Here, in effect, all real production is a differential addition to a generalized measure of wealth.

However, real production of wealth can be treated as a balance. Assuming that the source of wealth is the nominal (non-inflation-adjusted) production of wealth $\hat{P}$, then this source is balanced by a sink for wealth $\gamma C$, where $\gamma$ represents the rate at which wealth is lost to decay (Garrett, 2011)

$$\frac{dC}{dt} \equiv P = \hat{P} - \gamma C \tag{18}$$

so that

$$\gamma \equiv \frac{\hat{P} - P}{C} = \frac{\hat{P} - P}{\int_0^t P\,dt'} \tag{19}$$

Similarly, the rate $\beta$ at which wealth $C$ leads to nominal production $\hat{P}$ can be defined by

$$\beta \equiv \frac{\hat{P}}{C} = \frac{\hat{P}}{\int_0^t P\,dt'} \tag{20}$$

In this case, from Eq. (18), the growth of wealth can be expressed as a balance between a source and a sink of wealth

$$\frac{dC}{dt} = (\beta - \gamma)\, C \tag{21}$$

This is just an alternative expression for Eq. (10) with the rate of return on wealth $\eta$ replaced by the difference between the coefficient of nominal production $\beta$ and the coefficient of decay $\gamma$

$$\eta = \beta - \gamma \tag{22}$$





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The advantage of applying this treatment is that it leads to a very simple expression for inflation $i$ in Eq. (17)

$$i = \frac{\int_t^{t+\Delta t}\left(\hat{P}-P\right)dt'}{\int_t^{t+\Delta t}\hat{P}\,dt'} = \frac{\int_t^{t+\Delta t}\gamma\,C dt'}{\int_t^{t+\Delta t}\beta\,C dt'} = \frac{\langle\gamma\rangle}{\langle\beta\rangle} \tag{23}$$

where brackets imply a mean over the time interval of calculation $\Delta t$, which is normally one year. Inflation is determined by the balance between the coefficients $\beta$ and $\gamma$ of production and decay.[2] If $\Delta t$ is one year, then the quantity $i\Delta t$ represents the difference between nominal and real GWP.

### 3.2 Thermodynamic accounting of decay

Now, what is shown is how the above fiscal arguments for inflation can be represented within the context of the generalized thermodynamic framework illustrated in Fig. 1. Global wealth can be related to thermodynamic flows through the constant $\lambda$, as framed by Eq. (8) and validated through observations (Table 1). From Eq. (2), thermodynamic work $w$ can be defined as the net growth rate in an interface $\Delta G$ that drives downhill thermodynamic flows at rate $a = \alpha\Delta G$.

[2] In practice, statistics for nominal and real GWP are normally provided in current and fixed-year currency, respectively, and therefore are in different units. Thus, for a given time period $\Delta t$ (say one year), $\gamma$ can be calculated from differences in the logarithmic rate of expansion for $\hat{P}$ and $P$, noting that $\ln(1+x) \simeq x$

$$\gamma = \frac{\hat{P}-P}{C} \simeq \frac{P}{C}\left[\frac{1}{P}\frac{d\left(\hat{P}-P\right)}{dt}\right]\Delta t \simeq \frac{P}{C}\frac{d\ln\left(\hat{P}/P\right)}{dt}\Delta t$$

Effectively $\left[d\ln\left(\hat{P}/P\right)/dt\right]\Delta t$ is the fractional inflation $i$ over period $\Delta t$. Then, since $\eta = P/C$, it follows that $\gamma = i\eta$ and $\beta = \eta + \gamma = (1+i)\eta$.



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Thus, from Eq. (9)

$$w = \frac{d\Delta G}{dt} = \eta\,\Delta G \tag{24}$$

Equation (9) dictates that, since $\lambda$ is a constant, the rate of return $\eta$ applies equally to thermodynamic flows $a$, the size of the interface that drives flows $\Delta G$, and wealth $C$. It follows that the thermodynamic analog for the economic growth equations given by Eqs. (18) or (21) is

$$\frac{d\Delta G}{dt} = \hat{w} - \gamma\,\Delta G = (\beta - \gamma)\,\Delta G \tag{25}$$

What this expresses is the details of how the interface shown in Fig. 1 grows. A flow of energy across the interace at rate $a = \alpha\Delta G = \lambda C$. This flow enables civilization to do "nominal" work to stretch the interface outward at rate $\hat{w} = \beta\Delta G$. By extension of Eq. (11), nominal work is the thermodynamic expression of nominal economic production through

$$\hat{P} = \frac{\alpha\,\hat{w}}{\lambda} = \frac{\alpha}{\lambda}\,\beta\,\Delta G \tag{26}$$

However, it is only the "real" portion of work $w = d\Delta G/dt$ that contributes to the net or real rate of interface growth: for real growth to occur, nominal work $\beta\Delta G$ must be sufficiently rapid to overcome natural decay $\gamma\Delta G$. Thus, real production $P$ is related the size of the interface $\Delta G$ through

$$P = \frac{\alpha}{\lambda}\,(\beta - \gamma)\,\Delta G \tag{27}$$

Expressed in this fashion, real economic production is a balance between two opposing thermodynamic forces shown in Fig. 1. There is an interface that connects civilization to available energy reservoirs. Flow across this interface arises from a consumption of primary energy resources. By consuming energy, civilization both sustains its current size and does nominal work to "stretch" outward the size of the interface at rate $\beta$. As



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the interface grows, it makes previously innaccessible or unknown reservoirs of high potential energy (such as oil, coal, uranium, etc.) newly available. It is by consuming and doing work that consumption accelerates.

However, this stretching only drives "nominal" growth. "Real" growth takes into account environmental pressures that erode the interface at rate $\gamma$. Such "predation" of civilization by the environment is due to a loss of matter as things fall apart. There are many forms of material loss. Photons are radiated through thermal heat loss; mass falls down due to gravitation, and electrons are redistributed due to chemical reactions. What matters from civilization's perspective is that this constant loss of material hinders gains from nominal work $\hat{w}$. This slows the growth of the interface $\Delta G$ that drives flows, and consequently it dampens growth in energy consumption $a$ and wealth $C$. Due to material loss, only net or real work is done at rate $w$.

If the coefficient of decay becomes greater than the coefficient of production, such that $\gamma > \beta$, then from Eq. (27), *nominal* production $\hat{P}$ may be positive, but *real* production $P$ is negative. Discussing negative real production would seem unusual (or impossible) from a traditional economic perspective. From the more physical framework discussed here, it is simply a consequence of environmentally driven decay being so large that, in sum, total wealth is in a state of collapse. From Eq. (18), $dC/dt < 0$, and from Fig. 1, the interface is shrinking inwards rather than growing outwards. Historically, and on more regional levels, this is in fact a fairly common scenario. From Eq. (23), all it requires is that there are economic hyper-inflationary pressures associated with a rate $i = \gamma/\beta$ that is greater than 100%.

### 3.3 Inflationary pressures and civilization resilience

Based on the above arguments, it is easy to see how natural disasters are often expected to be inflationary. If the decay coefficient $\gamma$ suddenly rises, then from Eq. (18), this expands the difference between nominal and real production, and from Eq. (23), this shock leads to inflation.





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However, inflation does not necessarily follow from increasing financial damages associated with environmental disasters. For example, hurricane damages along the Atlantic seaboard have risen over the past century, but it turns out that this has not been because of a long-term increase in hurricane intensity or frequency (i.e., $\gamma$). Rather, damages have increased because economic wealth has become increasingly concentrated at the coasts (Pielke et al., 2008). If total hurricane-related damages (i.e. $\gamma C$) are normalized by inflation-adjusted wealth (i.e. $C$), then the capacity of hurricanes to cause damage at rate $\gamma$ has in fact remained roughly steady. The point here is that, in order for inflationary pressures to take hold, there must be an increase not just in total damages $\gamma C$, but in the *coefficient* of decay $\gamma$.

What seems reasonable is to expect that the decay rate $\gamma$ will in fact change over coming decades due to the increasingly harmful effects from global warming. Impacts will be regionally specific, but extremely difficult to predict. In light of this, the approach taken here is to simplify representation of the global economic impacts of climate change by defining a global economic "resilience" to a logarithmic increase in atmospheric $CO_2$ concentrations

$$\rho = 1/\left(d\gamma/d\ \ln\,[CO_2]\right) \tag{28}$$

If civilization's resilience is high, then the coefficient of decay $\gamma$ responds weakly to logarithmically changing $CO_2$ levels.[3]

There have been estimates of the regional economic impacts from extremes in climate change (Patz et al., 2005; Leckebusch et al., 2007). It is not obvious how to appropriately scale these impacts to civilization as a whole when many of the effects will be sustained, global, and largely unprecedented. Recent statistics do not yet provide meaningful guidance either. Figures 2 and 3 indicate that there is, as yet, no global warming signal in $\gamma$ that produces an economic signal that can be meaningfully

[3]The logarithm of $CO_2$ concentrations is considered because the primary insulating gases responsible for climate warming, namely $CO_2$ and water vapor, have a longwave absorptance that varies roughly as the square root of their concentrations (Liou, 2002).





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distinguished from the noise. Thus far, our resilience has been sufficiently high to avoid any obvious global-scale economic impacts from climate change. At some point we may be able to use observations of $\gamma$ and $[CO_2]$ as guidance for calculating $\rho$. In the meantime, our true resilience can only be supposed.

The hypothesis that is proposed here is that the effect on society of elevated levels of atmospheric $CO_2$ will be akin to a prolonged natural disaster. From the standpoint of the economic model discussed above, the effect will be to steadily increase the coefficient of decay $\gamma$ without changing the coefficient of nominal production $\beta$. From Eq. (23), this will appear economically as an inflationary pressure that impedes the growth in wealth $C$, as described by Eq. (21). In a phase space of $[CO_2]$ and $P$, the trajectory of civilization will depend on the resilience $\rho$ of civilization to elevated carbon dioxide levels: it is our resilience that will determine the strength of climate's negative feedback on economic growth.

## 4 The Climate and Thermodynamics Economic Response Model (CThERM)

The following section introduces a simplified framework for forecasting the evolution of civilization in a phase space of $[CO_2]$ and $P$, for a variety of assumed values of $\rho$. The Climate and Thermodynamics Economic Response Model (CThERM) couples a prognostic economic model to atmospheric $CO_2$ concentrations, as illustrated in Fig. 4. The prognostic economic module has just three coupled dynamic equations for wealth $C$, atmospheric $CO_2$ concentrations $[CO_2]$, and the rate of return $\eta$. From Eq. (9), wealth grows at rate

$$\frac{dC}{dt} = \eta C \tag{29}$$

The balance between anthropogenic emissions $E = \lambda c C$ (Eq. 15) and natural sinks is

$$\frac{d\,[CO_2]}{dt} = E - \sigma\,\Delta\,[CO_2] \tag{30}$$



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where $E = \lambda c C$ (Eq. 15) and $\sigma$ is an assumed linear sink rate on perturbations $\Delta[CO_2] = [CO_2] - [CO_2]_0$ above some preindustrial baseline. The modeling approach here is aimed at the simplest of possible approaches. In reality, the carbon cycle is much more complicated than can be easily justified by a linear sink model (Cox et al., 2000; Canadell et al., 2007). That said, even the current magnitude of the $CO_2$ sink is not well constrained (Le Quéré et al., 2003). Given current uncertainties, assuming a linear sink that is in line with current observations appears to provide long-range forecasts of $[CO_2]$ that are in good agreement with far more sophisticated models. More detailed discussion is presented in Sect. 4.3 and Appendix A.

From Eqs. (22) and (28), the rate of return $\eta$ changes at a rate given by

$$\frac{d\eta}{dt} = \frac{d\beta}{dt} - \frac{1}{\rho}\frac{d \ln [CO_2]}{dt} \tag{31}$$

Model trajectories in wealth $C$ and atmospheric carbon dioxide concentration evolve subject to initial conditions in $[CO_2]$, $C$, $\beta$ and $\gamma$. Note that global production $P$ is a diagnostic quantity given by Eq. (10).

The prognostic CThERM model expressed by Eqs. (29) to (31) is incomplete because it lacks prognostic equations for the carbonization of the world's wealth $c = E/(\lambda C)$ (Eq. 15) and the coefficient of nominal production $\beta = \hat{P}/C$ (Eq. 20). A more sophisticated model will need to address the evolution of these terms.[4]

A hindcast simulation that illustrates the accuracy of the model framework is shown in Fig. 5. The hindcast is initialized in 1985 and, based on results shown in Fig. 2, it is assumed that $d\gamma/dt = 0$ and that $d\beta/dt$ evolves on a linear trajectory that is consistent

[4]In principle, the evolution of $\beta$ is governed by two factors, as illustrated in Fig. 1. As civilization or any other system grows, it depletes known available energy reservoirs; at the same time, it expands into new reservoirs that were previously unavailable or unknown. Past bursts in growth in $\eta = \beta - \gamma$ are seen to have occurred around 1880 and 1950, perhaps due to a sudden increase in availability of important new oil reservoirs (Garrett, 2011). Presumably the future availability of energy reservoirs will influence the value of $c$ as well (Sorrell et al., 2010).





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with what is observed for the period between 1970 and 1984. A linear fit for $d\beta/dt$ is 0.017% $yr^{-1}$ per year with a 95% confidence limit of ±0.01% $yr^{-1}$ per year. A second source of uncertainty is associated with the $CO_2$ sink coefficient $\sigma$, which is estimated to have a value of $1.55 \pm 0.75$ % $yr^{-1}$ (Appendix A).

Figure 5 shows that, with these assumptions, the mid-range of hindcasts over a 23 year period between 1985 and 2008 faithfully reproduces both the timing and magnitude of observed changes in atmospheric $CO_2$ concentrations and global economic production $P$. The implication is that, even though the model that is used is extremely simple, it is nonetheless able to make accurate multi-decadal forecasts for growth of the global economy and atmospheric composition. Furthermore it suggests some ability of the model to explore thermodynamically constrained forecasts in a space of $P$ and $[CO_2]$ for a range of hypothetical values of civiilization resilience $\rho$ and decarbonization rates $-d \ln c/dt$.

As discussed previously, there is no good guidance yet for what a suitable choice for the resilience $\rho$ might be, and no prognostic model is included here for forecasting the evolution of either carbonization $c$ or the nominal productivity coefficient $\beta$. Thus, while the CThERM model is thermodynamically constrained, it can still only provide forecasts for a range of hypothetical scenarios in these parameters. In what follows, two main categories of scenarios are considered.

### 4.1 Forecast scenario A: no decarbonization

The first scenario that is considered here is simply to assume that for the remainder of this century, there will be no further decarbonization and the coefficient of nominal production is stagnant, i.e., $dc/dt = 0$ and $d\beta/dt = 0$. Figure 6 shows examples of forecasts for these conditions for the years between 2009 and 2100. Also shown for historical reference are past measurements between 1 AD and 2008 (Appendix B).

For this scenario, a range of resilience sub-scenarios can be considered. If civilization is so resilient that it is unaffected by elevated $CO_2$ levels, then the world economy $P$ sustains recent growth rates of 2.2% per year. By 2100, it increases by nearly an





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order of magnitude to a value of nearly 300 trillion 1990 dollars per year. The accumulated production of wealth $C \equiv \int_0^{2100} P dt'$ corresponds to an increase in rates of energy consumption $a = \lambda C$ from 16 TW in 2008 to 126 TW in year 2100. Absent any decarbonization, the accumulated and accelerating emissions push $CO_2$ levels above 1100 ppmv.

If, however, civilization has an extremely low resilience to elevated $CO_2$ levels, then the decay coefficient $\gamma$ increases by 5% $yr^{-1}$ per $CO_2$ doubling. Eventually, the decay coefficient exceeds the coefficient of nominal production $\beta$. In this case, economic production shrinks due to the impacts of climate change. Well before the year 2100, the inflationary pressure exceeds 100%: real GDP is negative and civilization is in a phase of collapse. However, even in this scenario, energy consumption rates peak at 89 TW in 2056 and although they fall to 21 TW in year 2100, they still exceed current levels. Because rates of energy consumption remain high, even with rapid and immediate civilization collapse, $CO_2$ levels still continue their rise to approximately 600 ppmv by year 2100.

What is perhaps most striking when looking at these forecasts is that we can expect some extraordinarily rapid near-term changes in the global economy and atmospheric composition. For any plausible resilience condition, atmospheric $CO_2$ concentrations and civilization GWP will change by as much in the next 40 years as they have in the past two thousand.

### 4.2 Forecast scenario B: rapid decarbonization

Although there is no evidence that civilization is in fact decarbonizing (Raupach et al., 2007), one can imagine for the sake of illustration a second forecast scenario shown in Fig. 7 in which $\beta$ stays constant, but the carbonization of civilization $c$ drops extremely rapidly. Supposing that carbonization $c$ halves in just 50 years, the value of $c$ ends up 73% lower in 2100 than it is at present. This is highly imaginary, of course. If nothing else, no consideration is made here of the costs of decarbonizing that would





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be involved. These would presumably act to lower $\beta$ and be an inflationary pressure themselves (Eq. 23). However, it is worth considering because, for one, it illustrates how extremely rapid decarbonization would need to be to lower $CO_2$ concentrations to something that only moderately exceeds the 450 ppmv levels that might be considered to be "dangerous" (Hansen et al., 2007). If civilization's resilience to climate change is extremely low, then only a combination of rapid civilization collapse and high decarbonization comes close to achieving a 450 ppmv goal. Otherwise, if civilization's resilience to climate change is extremely high, then emissions increase from 3.95 ppmv equivalent per year in 2008 to 8.64 ppmv per year in 2100.

The reason why even rapid decarbonization still corresponds with increasing emissions rates is that it has the side benefit of aiding economic health and growth. By slowing growth in $CO_2$ concentrations, the worst impacts of future climate change are constrained. Energy consumption is fundamentally linked to the size of civilization through the constant $\lambda$ (Eq. 8). Thus, any improvement to economic wealth corresponds to increased energy consumption and more rapid growth in $CO_2$ emissions (Eq. 16).

It is counter-intuitive, but comparing two scenarios with very low resilience to climate change, energy consumption rates rise about twice as fast with rapid decarbonization as with no decarbonization. The reason is that decarbonization aids society health, and this means greater energy consumption, which then leads to a partial offset of any environmental gains from decarbonizing in the first place.

### 4.3 Comparison with SRES scenarios

Figures 6 and 7 include for comparison's sake the phase space of $P$ and $CO_2$ concentrations that are employed in several well-known IPCC Special Report on Emissions Scenarios (SRES) illustrative marker scenarios (IPCC, 2007a). These scenarios provide statistics through 2100 for global GWP in 1990 MER US dollars along with global $CO_2$ emission rates from fossil fuel combustion. For the sake of consistency





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with CThERM calculations, atmospheric $CO_2$ concentrations are calculated from the second CThERM equation given by Eq. (30). Across the scenarios, calculated trajectories in $CO_2$ concentration perturbations are lower than those presented in the IPCC Third Report for the same emission rates, but calculated using the sophisticated "Bern" carbon cycle model (Joos et al., 1996). Part of this discrepancy may be because no consideration is made for the small additional perturbations in anthropogenic $CO_2$ emissions that come from future non-fossil fuel sources. But also, no account is made for possible future saturation of $CO_2$ sinks (Le Quéré et al., 2007). Regardless, the agreement is still sufficiently favorable to support using the extremely simple $CO_2$ sink model in Eq. (30) as an accessible, if conservative, substitute for the more sophisticated approaches used by the IPCC.

The comparisons between the CThERM and SRES scenarios are grouped according to whether or not decarbonization is included in the forecasts. CThERM trajectories in Fig. 6 include no decarbonization, and are paired with the A1F1 and A2 scenarios. These two SRES storylines are both based on a fossil-fuel reliant economy, while A1F1 has faster economic growth. For contrast, the CTheRM trajectories in Fig. 7 do include decarbonization, and are paired with the A1T, B1 and B2 scenarios. These storylines all include a switch to less carbon intensive fuels, but with a range of speeds of economic development.

Regardless of the precise scenario that is considered, there is a basic difference between the CThERM forecasts and the SRES scenarios. Each SRES scenario greatly underestimates how much atmospheric $CO_2$ concentrations will rise for a given level of global GWP. Or, put another way, SRES scenarios produce an unphysical overestimate of the wealth society can have while maintaining $CO_2$ levels below some nominal threshold. For example, the "environmentally sustainable" B1 scenario suggests that a $CO_2$ level below 500 ppmv is plausible by the end of this century, while maintaining a GWP of 360 Trillion 1990 US dollars per year. The CThERM results suggest that this combination simply cannot happen because, even with rapid decarbonization, sustaining this level of economic activity would require too much energy consumption. It is only with rapid decarbonization and civilization collapse that such $CO_2$ concentrations can be attained.

Perhaps the basic reason that there is a mismatch between the CThERM and SRES scenarios is that the SRES scenarios are based on an assumption that increases in energy efficiency will lower the amount of $CO_2$ emitted for a given amount of economic activity. The thermodynamic and observational analysis described here and in Garrett (2011), if it is correct, indicates that the opposite should be expected to hold. From Eq. (3), gains in efficiency $\epsilon$ accelerate $CO_2$ emissions by accelerating civilization's capacity to access primary energy reservoirs.

## 5 Conclusions

This study builds on a key result presented in a prior article (Garrett, 2011), that civilization wealth and global rates of primary energy consumption are tied through a constant value of $\lambda = 9.7 \pm 0.3$ mW per 1990 US dollar. On this basis, a very simple prognostic model (CThERM) is introduced for forecasting the coupled evolution of the economy and atmospheric $CO_2$ concentrations. While the model in its basic form has just three prognostic equations, it nonetheless provides accurate multi-decadal hindcasts for global world production and atmospheric concentrations of $CO_2$.

The much more sophisticated formulations commonly used in Integrated Assessment Models can have hundreds of equations. In part this is required to forecast regional variations of specific societal indicators such as population or standard of living. The argument made here and in Garrett (2011) is that, at the global scales relevant to atmospheric composition, such complexity is largely unnecessary. Both the global economy and atmospheric $CO_2$ can be considered to be "well-mixed", and they evolve in a manner that is constrained by the global rate of primary energy consumption.

One implication of this result is that a warming of the global climate should be expected to manifest itself economically as a long-term increase in global inflationary pressures. Environmental pressures erode a material interface that enables civilization



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to consume the primary energy resources it requires. Normally, this erosion is more than offset by increasing access to primary energy reservoirs; in fact, it is an increasing access to energy supplies that has enabled a positive (and growing) inflation-adjusted gross world product, and has led to the generally high standard of living we enjoy today. However, in a global warming scenario, it can be expected that environmental pressures will increase, and these will act to slow the growth of energetic flows. Fiscally, this will appear as an inflationary drag on growth of economic wealth, and ultimately this will push civilization towards an accelerating decline.

There are important differences between the thermodynamically-constrained long-range forecasts of the evolution of GWP and atmospheric $CO_2$ concentrations from CTheRM, and those seen in the commonly used IPCC SRES scenarios. Foremost, it looks as if the SRES scenarios make unphysical underestimates of the amount of energy consumption and $CO_2$ emissions that is required to sustain prosperity growth. Rather, it looks like the options for stabilizing $CO_2$ concentrations are tightly constrained. In fact, no physically plausible scenario leads to concentrations below the 450 ppmv level that might be considered as "dangerous" (Hansen et al., 2007).

One route for constraining $CO_2$ growth is to reduce the growth rate of wealth. This can be done by slowing the technological advancements that would enable society to grow into new energy reservoirs. Alternatively, society could increase its exposure to environmental predation. Unfortunately, both of these options necessitate inflationary pressures, so it is hard to see how democratically elected policy makers would willingly prescribe either of these things.

Otherwise, civilization must rapidly de-couple its growth from $CO_2$ emitting sources of energy. There is an important caveat however, which is that such decarbonization does not slow $CO_2$ accumulation by as much as might be anticipated. Decarbonizing civilization promotes civilization wealth by alleviating the rise in dangerous atmospheric $CO_2$ levels. But if the growth of wealth is supported, then energy consumption accelerates, and this acts to accelerate $CO_2$ emissions themselves. Thus, civilization appears to be in a double-bind with no obvious way out. Only a combination of extremely rapid





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decarbonization and civilization collapse will enable $CO_2$ concentrations to be maintained below 500 ppmv within this century.

# Appendix A

## Parameterization of a linear sink term for $CO_2$

A portion of the anthropogenic $CO_2$ that is accumulating in the atmosphere has a concurrent sink to the land and oceans, both from natural processes and changes associated with land-use. The nature of the sink is complex, and depends on multiple processes with timescales that vary by orders of magnitude. Detailed assessments of the magnitude, trends, and uncertainties in the airborne fraction of $CO_2$ emissions $E$ are provided by Canadell et al. (2007), and ideally would require a fully coupled Earth System Model (Gent and Co-authors, 2009).

For the sake of simplicity of argument, the carbon dioxide sink is assumed here to be a linear function of the disequilibrium in atmospheric $CO_2$ concentrations $C$. To see why this might not be as terrible a choice as it might initially appear, consider the simple analytic representation of a detailed carbon cycle model (Joos et al., 1996), which shows that a small pulse of $CO_2$ into the atmosphere decays over multiple timescales (Hansen et al., 2007):

$$CO_2\ (\%) = 18 + 14\, e^{-t/420} + 18\, e^{-t/70} + 24\, e^{-t/21} + 26\, e^{-t/3.4} \tag{A1}$$

This formulation points to multiple sink coefficients with decay weighted towards shorter timescales, meaning that recent, faster emissions decay at a more rapid rate than older, slower contributions. Thus, super-exponential (i.e. the exponent of an exponent) emissions growth would progressively bias the instantaneous, or effective, value of the sink rate to ever shorter timescales. If, however, $CO_2$ emissions grow nearly at a logarithmically constant rate, then the linear sink rate for these $CO_2$ emissions $\sigma$ (Eq. 30) should be approximately constant with time.



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Currently, $CO_2$ emissions growth is nearly exponential, so assuming that $\sigma$ is nearly constant, its value can be estimated by combining data for the ocean and land sink (Le Quéré et al., 2003) with an assumed pre-industrial equilibirum concentration of 275 ppmv (Wigley, 1983). This leads to an approximate value for $\sigma$ of $1.55 \pm 0.75\%$ per annum, corresponding to a sink timescale of about 65 years (Table A1).

The above framework neglects changes in $CO_2$ sinks that might be expected to change in the future if, for example, there is saturation of the ability of the earth's ecosystems and oceans to uptake carbon (Cox et al., 2000; Le Quéré et al., 2007). Certainly the systems involved are complex and this adds to the difficultly of making confident quantification of future behavior. Simply estimating a constant linear sink coefficient for atmospheric $CO_2$ based on recent observations is aimed more at simplicity than accuracy, and certainly more sophisticated forecasts than presented here could implement some functional dependence for $\sigma([\Delta CO_2])$. However, given that there are such large uncertainties on even the current magnitude of the $CO_2$ sink, assuming a linear sink coefficient seems adequate until estimates of carbon fluxes can be further constrained.

## Appendix B

### Historical records of economic production and $CO_2$ concentrations

Historical measurements of atmospheric $CO_2$ perturbations from an assumed baseline of 275 ppmv are shown in Fig. A1. Measurements come from a combination of in-situ measurements from Mauna Loa (Keeling and Whorf, 2005), and Antarctic ice core data from the EPICA Dome C (Flückiger et al., 2002) and the Law Dome (Etheridge et al., 1996). These data are compared to a time series for measurements of global world production that is derived from a combination of statistics in 1990 market exchange rate dollars available since 1970 (UNs, 2010) and more intermittent, long-term historical estimates for the years 0 to 1992 derived by (Maddison, 2003). For details see Garrett



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(2011). Although it is unclear exactly why, the two millennia data in production $P$ and and $[\Delta CO_2]$ are well-represented by a remarkably simple power-law fit that accounts for 90% of the variance ($r = 0.952$)

$$[\Delta CO_2] = 2.5\, P^{0.61}$$

The results suggest a fairly long term anthropogenic influence on atmospheric composition. It might be tempting to infer from these data that $CO_2$ measurements at Mauna Loa could be used to gauge the size of the global economy. However, obviously the observed relationship between $[\Delta CO_2]$ and $P$ must break down sometime in the future. $P$ is an instantaneous quantity, whereas $CO_2$ perturbations decay over timescales of hundreds to thousands of years (Eq. A1).

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**Table 1.** Measured values for the global rate of energy consumption $a$ (TW), global wealth $C$ (trillion 1990 US $), $CO_2$ emissions rates $E$ (ppmv yr$^{-1}$), the hypothesized constant parameter $\lambda$ (mW per 1990 US $) and $\lambda c$ (ppmv yr$^{-1}$ per $10^{15}$ 1990 US $) where $c = E/a$.

| | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2008 |
|---|---|---|---|---|---|---|---|---|---|
| $a$ (TW) | 7.2 | 8.4 | 9.6 | 10.3 | 11.7 | 12.2 | 13.2 | 15.3 | 16.4 |
| $C = \int_0^t P(t')\,dt'$ | 821 | 884 | 960 | 1048 | 1151 | 1266 | 1398 | 1536 | 1656 |
| $\lambda = a/C$ | 8.8 | 9.4 | 10.0 | 9.8 | 10.2 | 9.6 | 9.4 | 9.9 | 9.9 |
| $E$ | 1.91 | 2.17 | 2.50 | 2.56 | 2.88 | 2.99 | 3.16 | 3.74 | 4.00 |
| $\lambda c = E/C$ | 2.3 | 2.4 | 2.6 | 2.4 | 2.5 | 2.4 | 2.3 | 2.4 | 2.4 |

**Table A1.** Estimates of the annual ocean and land net sink for carbon (in Pg C $yr^{-1}$), including those associated with land-use changes (Le Quéré et al., 2003), the total sink (in ppmv $CO_2$ $yr^{-1}$), the decadal mean value of the carbon dioxide disequilibrium above 275 ppmv [$\Delta CO_2$], and the associated linear sink coefficient $\sigma$ (% $yr^{-1}$). For convenience, the total sink is expressed in units of ppmv atmospheric $CO_2$ per year through division by the total atmospheric mass (Trenberth, 1981), such that 1 ppmv $CO_2$ = 2.13 Pg emitted carbon.

| | Ocean sink | Land sink | Total sink (in ppmv $CO_2$ $yr^{-1}$) | [$\Delta CO_2$] | $\sigma$ (% $yr^{-1}$) |
|---|---|---|---|---|---|
| 1980s | $1.8 \pm 0.8$ | $0.3 \pm 0.9$ | $1 \pm 0.6$ | 70 | $1.4 \pm 0.9$ |
| 1990s | $1.9 \pm 0.7$ | $1.2 \pm 0.8$ | $1.5 \pm 0.5$ | 85 | $1.7 \pm 0.6$ |



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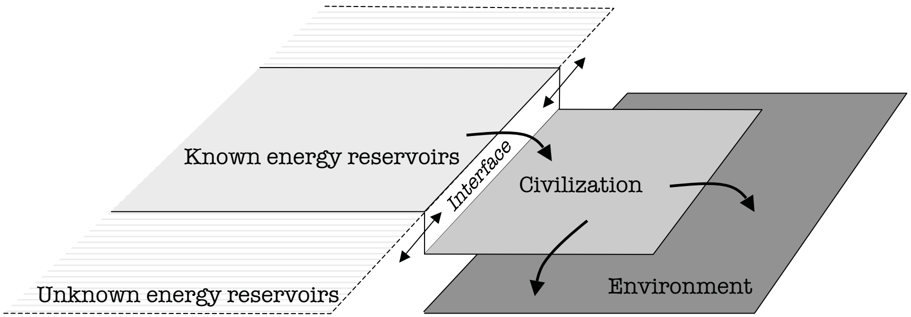


**Fig. 1.** Schematic for the thermodynamic evolution of civilization. Energy reservoirs, civilization, and the environment lie along distinct constant potential surfaces. The size of an interface between the surfaces determines the speed of downhill material flow. The interface itself grows or shrinks according to the net material flux convergence into civilization. Civilization growth expands flows by extending civilization's access to previously unknown energy reservoirs.





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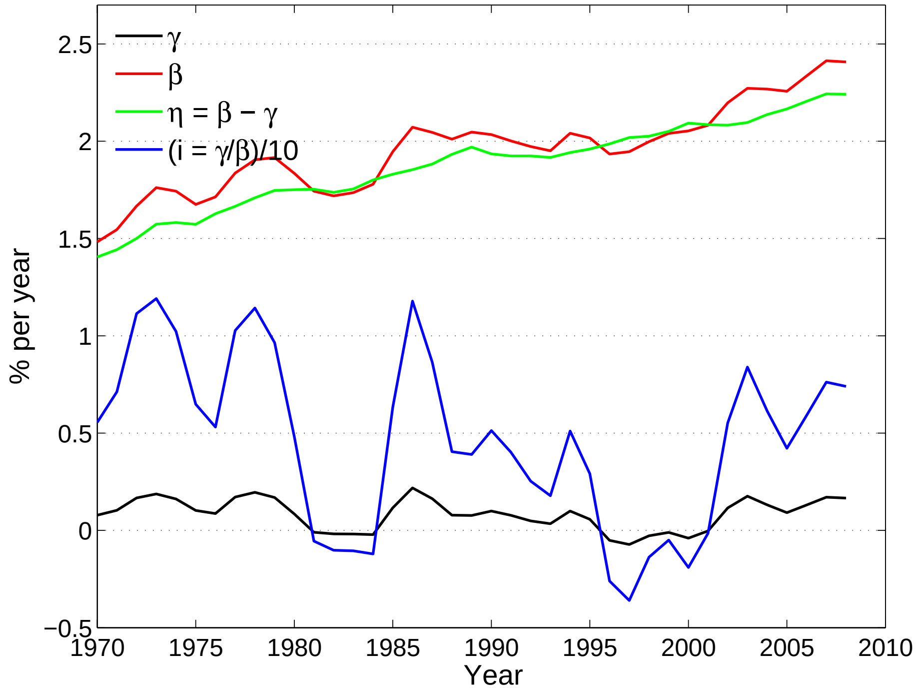


**Fig. 2.** From global economic statistics (UNs, 2010), derived global values for global inflation $i$ (Eq. 23), the decay coefficient $\gamma$ (Eq. 19), the source coefficient $\beta$ (Eq. 20) and the rate of return $\eta$ (Eq. 22) based on observations of nominal and real production, and total global wealth.





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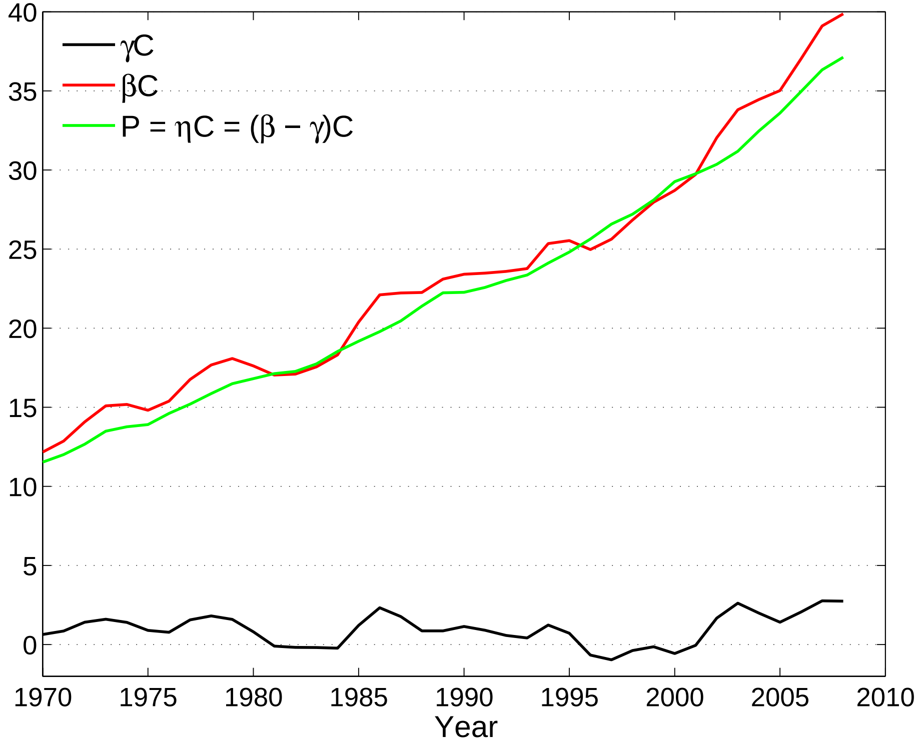


**Fig. 3.** As for Fig. 2 but for the product of the rate coefficients and total wealth $C$ (Eq. 7). The difference between $\beta C$ and $\eta C$ is the inflationary depreciation associated with each year $\gamma C$. (Eqs. 18 and 22).





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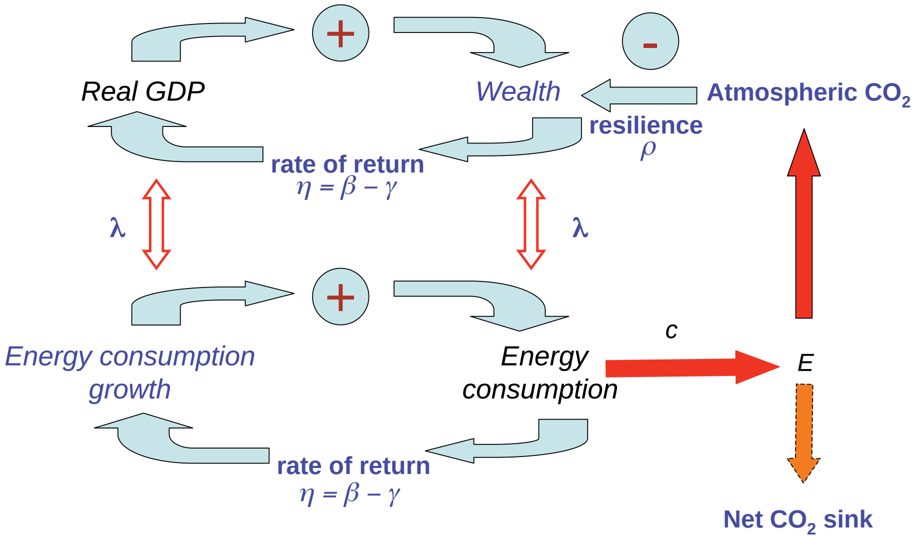


**Fig. 4.** Schematic illustrating the CThERM framework for economic growth (Garrett, 2011), coupled to atmospheric $CO_2$ concentrations. Global rates of primary energy consumption rates $a$ are tied to accumulated inflation-adjusted global economic wealth $C = \int_0^t P dt'$ through a constant coefficient $\lambda = 9.7$ milliwatts per 1990 dollar. Because $\lambda$ is a constant, growth in energy consumption rates $da/dt$ are represented economically by the real, inflation-adjusted global GDP $P$. Thus, $da/dt = \lambda P$ is the "rate of return" $\eta$ adding to $a = \lambda C$. $E$ represents the anthropogenic rate of $CO_2$ emissions, $\beta$ is the source for a positive rate of return $\eta$ due to increasing availability of energy reservoirs. $\gamma$ is the sink for civilization growth driven by environmental degradation. Emissions $E$ determine $CO_2$ concentrations, subject to land and ocean sinks. $CO_2$ concentrations act as a negative feedback on economic growth.





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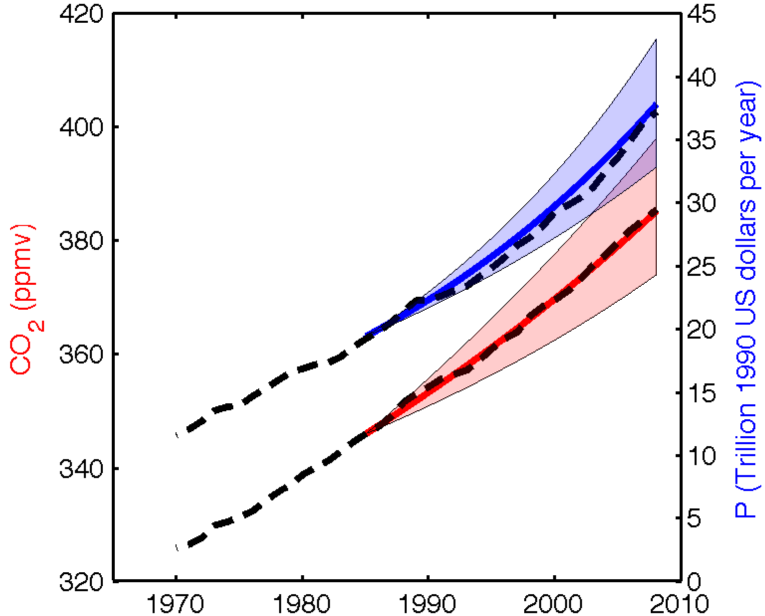


**Fig. 5.** Based on the CThERM model given by Eqs. (29) to (31), hindcast trajectories and associated uncertainty estimates for the period 1985 to 2008 in a space of atmospheric $CO_2$ concentrations (red) and global economic production (blue). Observed statistics for the period 1970 to 2008 are shown by black dashed lines. The model is initialized with observed conditions in 1985, and a linear trend in the nominal production coefficient $\beta$ between 1970 and 1984.





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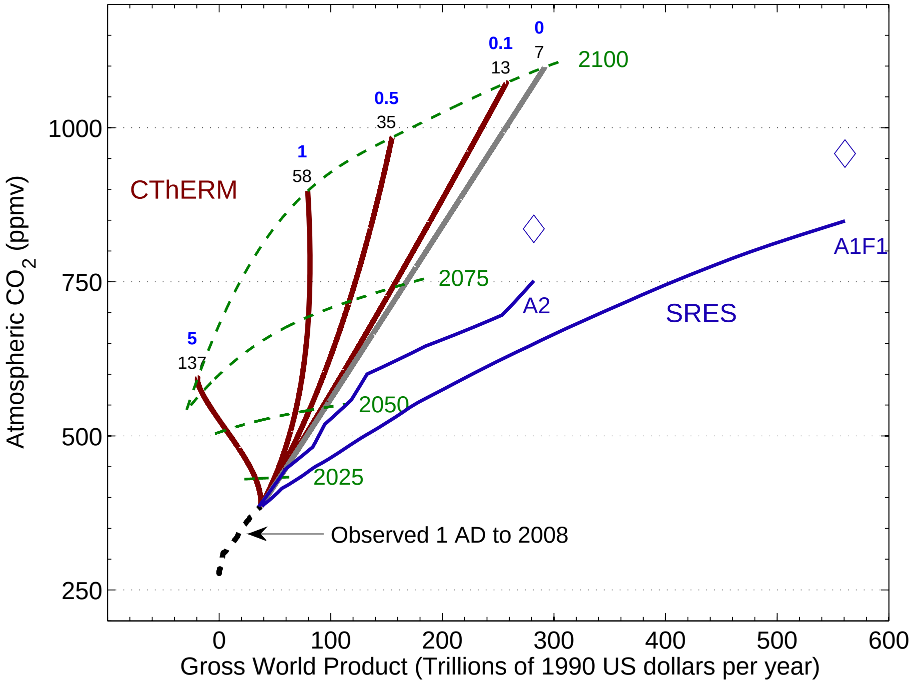


**Fig. 6.** As for Fig. 5, except for CThERM trajectories calculated out to 2100, with the model initialized with conditions in 2008 and assuming that $d\beta/dt = 0$ and $dc/dt = 0$ for a range of values of inverse resilience $1/\rho$ (blue numbers expressed in % $yr^{-1}$ change in the decay coefficient $\gamma$ per $CO_2$ doubling). Small numbers in black correspond to the calculated inflationary pressure $i = \gamma/\beta$ (Eq. 23) in year 2100. Green dashed lines represent the modeled year. Shown for comparison are the IPCC SRES A1F1 and A2 scenarios based on the CThERM linear sink model for $CO_2$. $CO_2$ concentrations for these scenarios using the Bern carbon cycle model are shown by blue diamonds. Historical data from 1 AD to 2008 is added for reference (see Appendix B).





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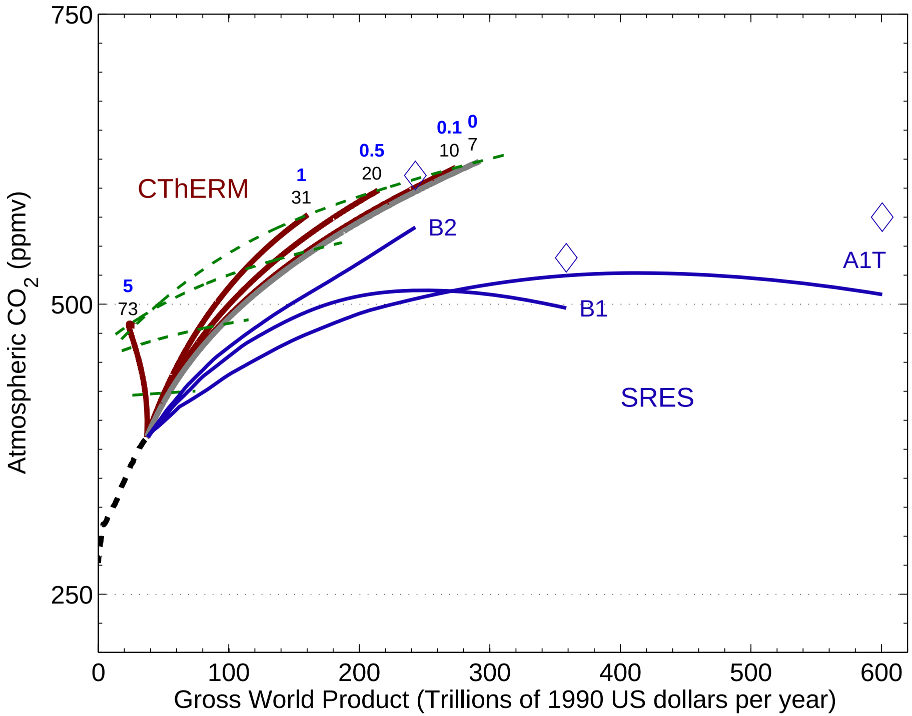


**Fig. 7.** As for Fig. 6 except that it is assumed that the value of carbonization *c* has an assumed halving time of 50 years. For comparison, the IPCC SRES trajectories that are considered are the A1T, B1 and B2 scenarios.





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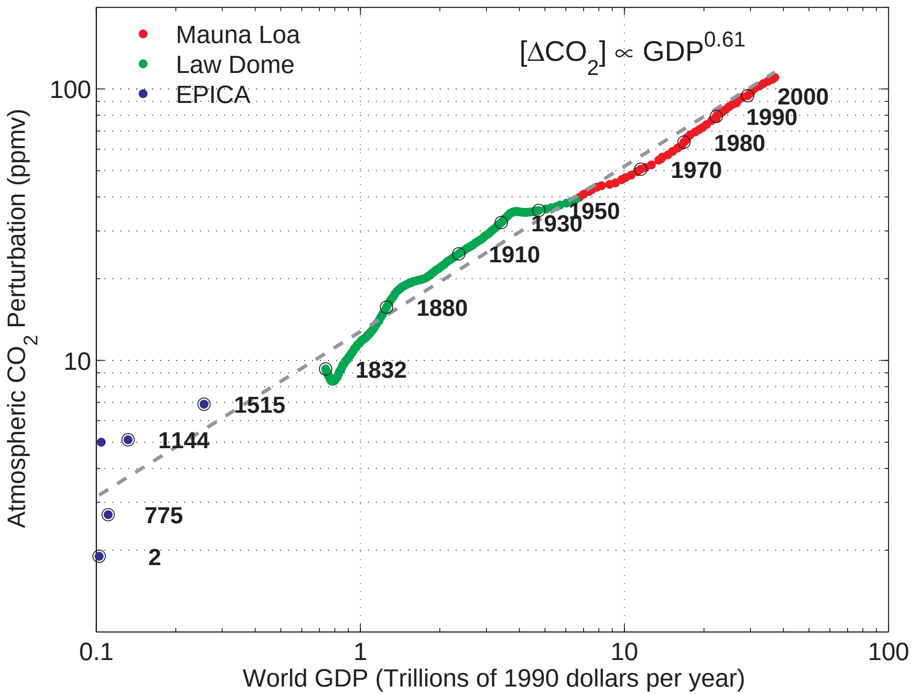


**Fig. A1.** Measured perturbations in atmospheric $CO_2$ concentrations from a baseline of 275 ppmv, compared with historical estimates of global GDP in inflation adjusted 1990 dollars, with associated year markers, and a linear fit to the data.





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