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Delay-induced rebounds in CO_2 emissions and critical time-scales to meet global warming targets

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Key Points:

- Intrinsic delays in the human-energy-climate system cause rebounds beyond peak CO_2 emissions
- Climate-friendly technologies must spread globally at unprecedented rates to meet the global warming targets

Supporting Information:

- Supporting Information S1

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Abstract While climate science debates are focused on the attainment of peak anthropogenic CO_2 emissions and policy tools to reduce peak temperatures, the human-energy-climate system can hold "rebound" surprises beyond this peak. Following the second industrial revolution, global per capita CO_2 emissions (c_c) experienced a punctuated growth of about 100% every 60 years, mainly attributable to technological development and its global spread. A model of the human-energy-climate system capable of reproducing past punctuated dynamics shows that rebounds in global CO_2 emissions emerge due to delays intrinsic to the diffusion of innovations. Such intrinsic delays in the adoption and spread of low-carbon emitting technologies, together with projected population growth, upset the warming target set by the Paris Agreement. To avoid rebounds and their negative climate effects, model calculations show that the diffusion of climate-friendly technologies must occur with lags one-order of magnitude shorter (i.e., ~6 years) than the characteristic timescale of past punctuated growth in c_c. Radically new strategies to globally implement the technological advances at unprecedented rates are needed if the current emission goals are to be achieved.

1. Introduction

For decades, climate research and policy focused on reducing global greenhouse gas emissions (E) to limit global warming to 2°C above preindustrial levels [*Meinshausen et al.*, 2009]. Current mitigation efforts remain well below expectations when judged by such global-climate targets. In 2015, a 1°C average warming was crossed in tandem with a 400-ppm atmospheric CO_2 concentration. However, the past 2 years appear to hold some positive news as E may have seemingly stabilized around a peak of 3.5×10^4 Mt CO_2 per year [*Jackson et al.*, 2016]. The optimism associated with the possibility of having reached a stabilization in E was also concomitant with the Paris Agreement that proposed a lowering of the target limit from 2°C to "well below 2°C" with an aspiration toward 1.5°C [*Hulme*, 2016]. As shown here, this optimism may be premature when extrapolations beyond peak E are analyzed in the context of delays in the human-energy-climate system. Scenarios prescribing future mitigation strategies decrease E in time (t) at a gradual rate starting from a set time t_m depending on technological and economic constraints [*Pfister and Stocker*, 2016]. In this framework, a delayed t_m and subsequent reduction in E results in higher global peak temperatures necessitating greater reductions in E to achieve the 1.5–2.0°C target [*Allen and Stocker*, 2013; *Pfister and Stocker*, 2016]. Any gradual reduction in E ignores the inherent inertia and endogenous delays encoded in the dynamics of its main constitutive terms when E is expressed as $E = c_c \cdot N$, where N is the global population and c_c the global per capita CO_2 emissions. Since the second industrial revolution (conventionally dated at 1870 [*Mokyr*, 1998]), c_c followed a punctuated growth (Figure 1b) with an apparent stabilization at present day (Figure 1c), while N exhibited faster than exponential growth [*Von Foerster et al.*, 1960; *Johansen and Sornette*, 2001; *Kaack and Katul*, 2013]. Using a novel modeling framework that reproduces past human-energy-climate dynamics, we show here that delayed dynamics in c_c results in 21st century warming exceeding the 2.0°C limit even if a policy decision is immediately taken to reduce E (i.e., $t_m = 2016$) and N stabilizes during the century (an unlikely outcome as discussed elsewhere [*Gerland et al.*, 2014; *Warren*, 2015]).

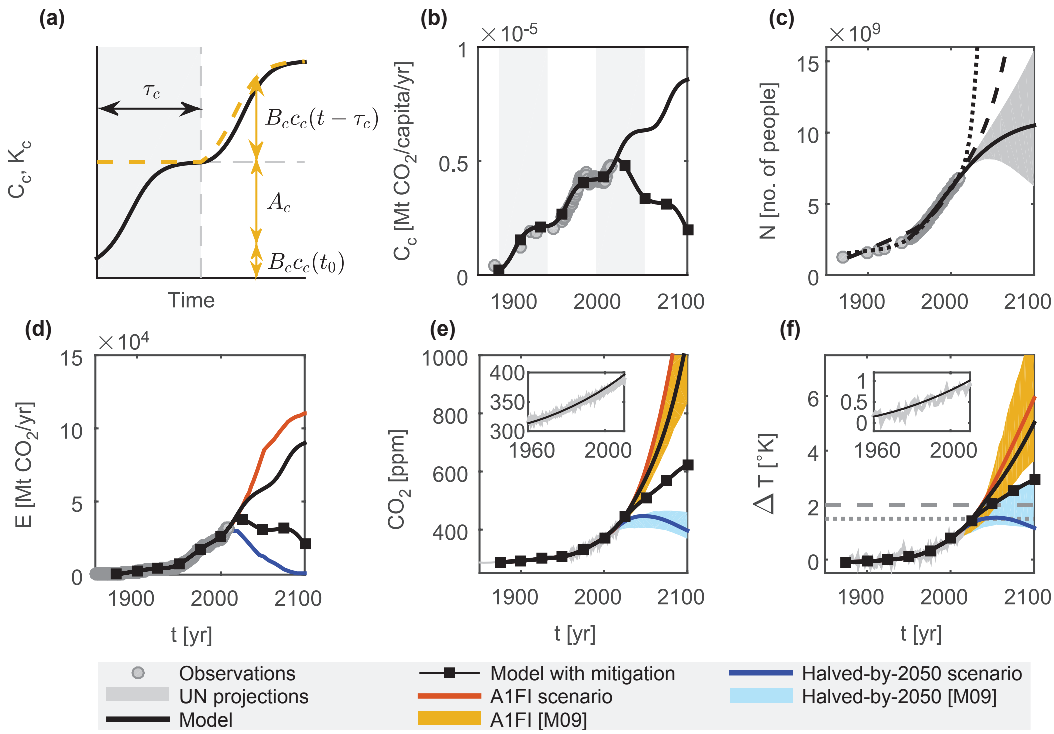

Figure 1. Punctuated evolution of anthropogenic emissions and the human-climate system. (a) Conceptual model of delayed growth of per capita emission c_c (solid line) and emission capacity K_c (dashed line): after a time τ_c, K_c increases by a factor $B_c c_c(t-\tau_c)$, where B_c is the relative increase rate and τ_c a time delay. Historical trends of (b) per capita c_c, (c) population N, (d) global CO_2 emissions E, (e) atmospheric CO_2 concentration, and (f) surface temperature anomaly ΔT (relative to the 1860–1899 period). The zero-dimensional model is compared with observed CO_2 and ΔT trends (inset in panels e and f) and the projections by *Meinshausen et al*. [2009] (M09) using a fossil fuel intensive (SRES-A1FI) and halved-by-2050 emission scenarios as forcing data (red and blue lines, respectively). The results of the fully coupled human-energy-climate model assuming logistic population growth are also illustrated for business as usual (i.e., $t_m = \infty$) and climate mitigation ($t_m = 2016$) scenarios (black line and black squares, respectively). In the case of emission reduction, climate-friendly technologies are assumed to spread at the same rate as past-observed fossil fuel technologies ($B_c = B_{c,m} = 1.05$, $\tau_c = \tau_{c,m}$ = 58 years), demonstrating that a much faster technology transfer is needed to achieve current warming targets by 2100. Different global population scenarios are also illustrated for comparison: a punctuated evolution [*Parolari et al*., 2015] and a log-periodic model that exhibits nonrandom oscillations and a finite-time singularity at year 2062 [*Johansen and Sornette*, 2001] (dashed and dotted lines in panel a, respectively).

2. Methodology

2.1. Punctuated Evolution of Anthropogenic Emissions

The chain of events leading to increased E was initiated in the 16th century by a transition from wood to coal in the U.K. [*Nef*, 1977]. Such a transition to an abundant energy source fueled the industrial revolution during the 1800. However, anthropogenic emissions began to appreciably impact climate after the second industrial revolution [*Mokyr*, 1998], when new technological developments increased carbon emissions by many energy-intensive sectors (e.g., transportation [*Fuglestvedt et al*., 2008]). Emerging economies (mostly China and India [*Le Quéré et al*., 2013; *Li et al*., 2016]) soon followed a similar path with a delay of ~60 years. This, together with an increasing exploitation of oil reserves (see Appendix S1, Supporting Information), partly explains the observed punctuated evolution in c_c (Figure 1b) from 1950 onward.

The description of such punctuated evolution of the human-energy-climate system starts by noting that the diffusion of innovations, that is, the fraction of population using a new technology, can be described by a logistic model [*Swan*, 1973]. In turn, the global average of per capita CO_2 emissions varies proportionally to the number of individuals with access to carbon-emitting technologies. Hence, a logistic dynamics for c_c can be expressed as $dc_c(t)/dt = r_c c_c(t)[K_c - c_c(t)]$, where r_c is a technology diffusion rate and K_c is a long-term per capita emission capacity representing the ability of an "average individual" to access energy resources that contribute to E. At the global level, adoption of new technologies exhibits a delay τ_c [*Fanelli and Maddalena*, 2012] associated with the time required for the formulation and implementation of policies, for infrastructure construction, for overcoming the resiliency of competing sectors (e.g., fossil fuel industry against renewable energies [*Showstack*, 2016]), and for bridging technological gaps among countries. The introduction of new energy production technologies thus contributes to continually changing the asymptotic value K_c leading to a punctuated evolution of c_c. Such delayed dynamics can be described by a time-delay capacity $K_c(t-\tau_c)$ that links the current K_c to the history of technological development at $t-\tau_c$. The $K_c(t-\tau_c)$ may be an increasing function, if the spreading of new technologies promotes CO_2 emissions (as in the case of coal and oil use being progressively adopted globally in the 19th and 20th centuries), or a decreasing one, if the technologies being introduced can be generically labeled as "green."

2.2. Beyond-Peak Anthropogenic Emissions

Beyond "peak" emissions (assumed to be $t > t_m$), existing scenarios impose declining global CO_2 emission rates, thereby implicitly assuming efficient spreading of renewable energy sources [*Barthelmie and Pryor*, 2014] and even negative emission strategies [*Smith*, 2015]. However, these technologies are developed in the world's leading economies and, similar to the historically observed spreading of industrialization, it is reasonable to assume that their global diffusion will occur with a delay depending on climate policies and international trade [*Popp*, 2011], as well as intrinsic societal inertia. To investigate the role of delays in c_c on future global warming scenarios, the coupled dynamics of $c_c(t)$ and $N(t)$ are used to construct realistic scenarios for $E(t)$ in which the diffusion of climate-friendly or green technologies offsets global fossil fuel consumption, but with lags. To a leading order, per capita emissions are expected to follow a path in which the timescale of technological diffusion is commensurate to past technological dynamics, with $K_c(t-\tau_{c,m})$ a decreasing function and $\tau_{c,m}$ a new time delay. Therefore, we start our analysis by initially assuming that the timescale of the progressive global diffusion of new technologies is an intrinsic property of the technological transfer process, and is thus valid for both the diffusion of carbon-emitting technologies (as observed in the past) and the spreading of green technologies (to be projected into the future). We then evaluate what changes in the coupled human-energy-climate system dynamics would be required to meet global warming targets by constructing emission scenarios with different delays $\tau_{c,m}$. Changes in E resulting from the compound dynamics of N and c_c are related to global climate temperature by means of a well-studied zero-dimensional coupled carbon [*Garrett*, 2012] and energy [*Knutti and Hegerl*, 2008] models as described next. By zero-dimensional, we mean a model that does not explicitly resolve spatial variability so that all budget equations are formulated for the entire globe composed of land–ocean–atmosphere reservoirs. On the one hand, a zero-dimensional approach does not describe in detail local/regional patterns of innovation, anthropogenic emissions, and climatic conditions. On the other, delays in globally averaged per capita emissions c_c arise from spatiotemporal gradients in the development and adoption of technologies. Such local/regional heterogeneities are thus captured by our approach through the global dynamics of technological transfer, which we model explicitly. This motivates our choice of a simple zero-dimensional model.

2.3. Human-Energy-Climate System Model

2.3.1. Per Capita Emissions

While c_c has been nearly steady over the last decade [*Garrett*, 2011, 2012], a plethora of factors influence its dynamics when viewed over a 100 years time frame. Here, a delayed differential equation (DDE) accounting for lags in diffusion of technologies is proposed and is given by:

$$\frac{dc_c(t)}{dt} = r_c c_c(t)\left[K_c\left(t-\tau_c\right) - c_c(t)\right] \quad for \quad t \le t_m, \tag{1}$$

where the delayed per capita emissions capacity K_c is defined as [*Parolari et al*., 2015]:

$$K_c\left(t-\tau_c\right) = A_c + \int_{t-\tau_c}^{t} B_c'\left(t'\right) c_c\left(t'\right) dt', \tag{2}$$

where A_c is a background capacity and $B_c'(t)$ is a time-delayed kernel. The simplest representation of delayed dynamics is obtained by choosing $B_c'(t) = B_c\delta\left(t-\tau_c\right)$ with δ being a Dirac delta function [*Yukalov et al*., 2009; *Parolari et al*., 2015], leading to:

$$K_c\left(t-\tau_c\right) = A_c + B_c \cdot c_c\left(t-\tau_c\right), \tag{3}$$

where B_c defines an increase in the ability of each individual to emit CO_2 relative to the history of the human-energy-climate system at time $t - \tau_c$ [*Yukalov et al.*, 2009; *Parolari et al.*, 2015]. The parameter B_c represents the impact of past policies and technology adoption at $t - \tau_c$ on the per capita emission capacity at time t, accounting for the exploitation of energy resources, the development of new technologies, and their delayed diffusion across political boundaries or along socioeconomic gradients. It is to be noted that functions other than $B'_c(t) = B_c \delta(t - \tau_c)$ can also be used by replacing the δ with smooth functions weighing differently the entire history from t_c to t (i.e., the function integrates to unity) while still reproducing punctuated growth with some "smearing." However, such functions require additional parameters that cannot be readily inferred from the limited data here, though the model still allows for their usage. The resulting DDE for $c_c(t)$ is known to exhibit rich dynamics (e.g., exponential and punctuated growth, self-generated oscillations, finite-time singularities, and death [*Yukalov et al.*, 2009; *Kaack and Katul*, 2013; *Parolari et al.*, 2015]), providing a novel framework for the description of past ($t \le t_m$), as well as projected (i.e., $t > t_m$), human–energy–climate interactions (Figures 1a and 1b). Equation (1) must be solved numerically using Equation (3) for $t > \tau_c$ and $K_c = A_c + B_c \cdot c_c(t_0)$ for $t \le \tau_c$ (where t_0 is the initial time).

2.3.2. Emission Scenarios

Beyond t_m, adoption of climate-friendly technologies is assumed to out-weight fossil fuel consumption and spread globally but with a lag. To investigate the effects of reduced E (through reduced c_c) on the climate system but maintaining the accepted N projections, observed c_c increases in the past are assumed to follow a punctuated evolution into the future with drops instead of jumps. Hence, future E scenarios through c_c (i.e., for $t \le t_m$) can be described by a transformation of Equation (1). Defining the transformation $T : c_c(t) \to \bar{c}_c(t) = c_c^* - c_c(t)$ that preserves continuity of c_c at $t = t_m$, and changing the sign of the right-hand side of Equation (1) for $t > t_m$ (to indicate the reduction in carbon emissions associated with the adoption of green technologies), leads to:

$$\frac{dc_c(t)}{dt} = -r_{c,m}\left[c_c^* - c_c(t)\right]\left\{K_c\left(t - \tau_{c,m}\right) - \left[c_c^* - c_c(t)\right]\right\} \; for \quad t > t_m, \tag{4}$$

where $c_c^* = c_c(t_0) + c_c(t_m)$ and $K_c(t - \tau_{c,m}) = A_c + B_{c,m} \cdot \left[c_c^* - c_c(t - \tau_{c,m})\right]$ for $t > t_m$ (defined by Equation (3) otherwise), being $B_{c,m}$ the relative K_c decrease, and $\tau_{c,m}$ a new time-delay. The transformation T is performed to ensure that, if mitigation is effective in reducing emissions as much as past fossil fuel consumption was effective in emitting carbon (i.e., same set of model parameters $r_{c,m} = r_c, A_{c,m} = A_c, B_{c,m} = B_c, \tau_{c,m} = \tau_c$), preindustrial conditions are reached within the same time frame of industrialization (see Appendix S1). The parameter $B_{c,m}$ encodes the reduction of per capita emissions due to the introduction of low-carbon emitting technologies, resulting in a punctuated decay of c_c to finite-time zero-emissions ($B_{c,m} \ge 1$) or to a stationary level ($0 < B_{c,m} < 1$). However, if green technologies fail to offset fossil fuel consumption due to economic (un)feasibility [*Koningstein and Fork*, 2014] effects, resembling rebound [*Greening et al.*, 2000; *Garrett*, 2012] can occur (punctuated oscillations for $B_{c,m} < 0$). Even though the solution of Equation (4) allows negative carbon emissions, negative per capita emissions are unlikely within the simulation time frame (1875–2100) and c_c is set to be nonnegative but still allowing $dc_c/dt < 0$.

2.3.3. Population Dynamics

Population N is described by the logistic model [*Kaack and Katul*, 2013]:

$$\frac{dN(t)}{dt} = r_N N(t)\left[K_N - N(t)\right], \tag{5}$$

where r_N is the growth rate and K_N is a finite carrying capacity assumed to be constant. The debate remains open on whether finite environmental resources (i.e., a finite carrying capacity) can sustain the observed faster-than-exponential growth [*Johansen and Sornette*, 2001; *Kaack and Katul*, 2013; *Parolari et al.*, 2015] Faster than exponential dynamics leads to finite-time singularities, clocking a possible regime shift—or a Doomsday [*Von Foerster et al.*, 1960]—in the mid-21st century (see Figure 1). A dynamical carrying capacity can also be used to account for degradation or improved resourcefulness on a densely populated planet together with lags between social and ecological dynamics [*Parolari et al.*, 2015]. Following the same approach used for c_c leads to a DDE for $N(t)$ with $K_N = A_N + B_N \cdot N(t - \tau_N)$.

2.3.4. Carbon Balance

The temporal dynamics of global CO_2 emissions from fossil-fuel burning is defined as before with $E(t) = c_c(t) \cdot N(t)$. The balance between E and global net sinks leads to a global budget for atmospheric CO_2 [*Garrett*, 2012]:

$$\frac{dCO_2(t)}{dt} = \mu E(t) - \sigma_c \left(CO_2, T\right) \cdot \Delta CO_2(t), \tag{6}$$

where μ is a conversion factor accounting for instantaneous dilution of CO_2 emissions in the total atmospheric mass (i.e., 1 ppmv CO_2 = 2.13 Pg emitted carbon C with 1 unit of C corresponding to 3.667 units of atmospheric CO_2 [*Garrett*, 2012]), $\sigma_c = \sigma_{c,l} + \sigma_{c,o}$ is a sink rate accounting for land ($\sigma_{c,l}$) and ocean ($\sigma_{c,o}$) carbon uptake, and $\Delta CO_2(t) = [CO_2(t) - CO_{2,0}]$ is a departure from a preindustrial baseline value $CO_{2,0}$ [*Garrett*, 2011, 2012]. Combining data for ocean and land sinks from 1980s and 1990s with a preindustrial equilibrium concentration of 275 ppmv, *Garrett* [2012] provide an estimate for σ_c of 0.0155 per year. The carbon balance in Equation (6) is a model of maximum simplicity [*Garrett*, 2012] though the sink term σ_c is regulated by complex carbon-cycle feedbacks occurring over several spatiotemporal scales [*Cox et al*., 2000; *Lenton*, 2000; *Le Quéré et al*., 2013]. The uptake rate of atmospheric CO_2 by land and ocean sinks did decline approximately by one third over the 1959–2012 period [*Raupach et al*., 2014] due to nonlinear responses of the land–ocean system to warming and increasing CO_2. Many carbon-cycle climate models suggest that the terrestrial carbon sink depends on a trade-off between photosynthesis and respiration: the biosphere can provide a negative feedback between increasing CO_2 and temperature until a threshold temperature is reached when biological respiration (increasing exponentially with T) exceeds the CO_2 fertilization effect [*Heimann and Reichstein*, 2008]. The ocean carbon sink depends on the concentration gradient of CO_2 between the atmosphere and the ocean but also on the solubility of CO_2. The CO_2 partial pressure increases exponentially with sea surface temperature [*Lenton*, 2000], thus reducing the CO_2 gradient driving the carbon sink from the atmosphere to the ocean. Therefore, increasing atmospheric CO_2 will enhance the sink but such a negative feedback is expected to saturate due to warming [*Lenton*, 2000]. These mechanisms are accounted for using a linear dependence between land carbon uptake on temperature and the saturation effect of increasing CO_2 on the ocean sink given by:

$$\sigma_{c,l} = \sigma^*_{c,l}\left[1 - \beta_l \Delta T\right], \tag{7}$$

$$\sigma_{c,o} = \sigma^*_{c,o}\frac{K_o}{K_o + \Delta CO_2}, \tag{8}$$

where $\sigma^*_{c,l}$ and $\sigma^*_{c,l}$ are the baseline sink rates, β_l is a fitting parameter, and K_o a half-saturation constant.

2.3.5. Surface Temperature

A zero-dimensional global energy-balance can be used to determine changes in the Earth surface temperature ΔT [*Schlesinger*, 1986]:

$$C_T\frac{d\Delta T(t)}{dt} = \Delta Q - G_0^{-1}\left(1 - f\right)\Delta T(t), \tag{9}$$

where C_T is the heat capacity of the upper ocean, ΔQ is the radiative forcing, G_0 is the zero-feedback gain of the climate system and f is a factor accounting for all the feedback mechanisms occurring within the Earth system (e.g., water vapor increase with warming, changes in lapse rate, albedo, and clouds) [*Schlesinger*, 1986; *Knutti and Hegerl*, 2008]. A typical value of the amplifying feedback f is 0.65 with a standard deviation of 0.13 [*Knutti and Hegerl*, 2008]. Accounting for the logarithmic dependence of the radiative forcing on atmospheric CO_2 [*Myhre et al*., 1998], the equilibrium solution of Equation (9) is [*Schlesinger*, 1986; *Jones et al*., 2003; *Knutti and Hegerl*, 2008]:

$$\Delta T_{eq}(t) = \frac{S_{2\times CO_2}}{ln(2)} \cdot ln\left[\frac{CO_2(t)}{CO_{2,0}}\right], \tag{10}$$

where the climate sensitivity $S_{2\times CO_2}$ for a doubling of atmospheric CO_2 is defined as [*Knutti and Hegerl*, 2008]:

$$S_{2\times CO_2} = \frac{\Delta T_0}{1 - f}, \tag{11}$$

where $\Delta T_0 = G_0 \Delta Q_{2\times CO_2} = 1.2°C$ the blackbody no-feedback response to the radiative forcing $\Delta Q_{2\times CO_2}$ resulting from a CO_2 doubling [*Schlesinger*, 1986; *Knutti and Hegerl*, 2008].The actual response of the climate system is given by the transient solution of Equation (9) [*Schlesinger*, 1986]:

$$\Delta T(t) = \Delta T_{eq}(t)\left[1 - e^{-t/\tau_e}\right], \qquad (12)$$

where $\tau_e = C_T G_0/(1-f)$ the e-folding time required for the climate system to reach equilibrium. This lag between the equilibrium warming ΔT_{eq} and the actual climate response is mainly due to the thermal inertia of the ocean [*Schlesinger*, 1986]. A wide range of τ_e values varying between 10 and 100 years has been estimated by energy balance, radiative-convective, and general circulation models. For the climate response to an abrupt increase in CO_2 concentration, coupled atmosphere–ocean models suggest that $\tau_e \sim 50-100$ years due to the transport of CO_2-induced surface heating into the interior of the ocean [*Schlesinger*, 1986]. The evolution of surface temperature is then calculated as $T(t) = T_0 + \Delta T(t)$, starting from $T_0 = T(1875) \approx 286.9°K$.

2.3.6. Simulations Setup

The resulting sets of differential equations for the zero-dimensional model are solved numerically with initial conditions set at year 1875, the transition from the first to the second industrial revolution. The human-climate-system model is calibrated using historical CO_2 concentration and surface temperature data as well as simulation results derived from fully coupled and spatially explicit global carbon-climate models [*Cox et al.*, 2000]. Historical data on population growth, anthropogenic emissions, global mean atmospheric CO_2 concentration, and surface temperature have been assembled from the literature (see Appendix S1 for details [*MacFarling Meure et al.*, 2006; *Maddison*, 2010; *Boden et al.*, 2011; *United Nations, Department of Economic and Social Affairs, Population Division*, 2015]). The authors digitized emission scenarios and projected CO_2 and temperature from the existing studies [*Jones et al.*, 2003; *Meinshausen et al.*, 2009].

3. Results and Discussion

The coupled human-energy-climate model is shown to agree with historical observations (Figures 1b–1f) when c_c and N are allowed to vary dynamically. After the second industrial revolution, the transition from wood to coal and from coal to oil (see Appendix S1), together with the delayed industrialization of developing countries, caused a global increase in K_c by 105% every $\tau_c = 58$ years (Figure 1b). These technological jumps in c_c-induced oscillations in E, but the amplitudes were buffered by the rapid growth in N (until

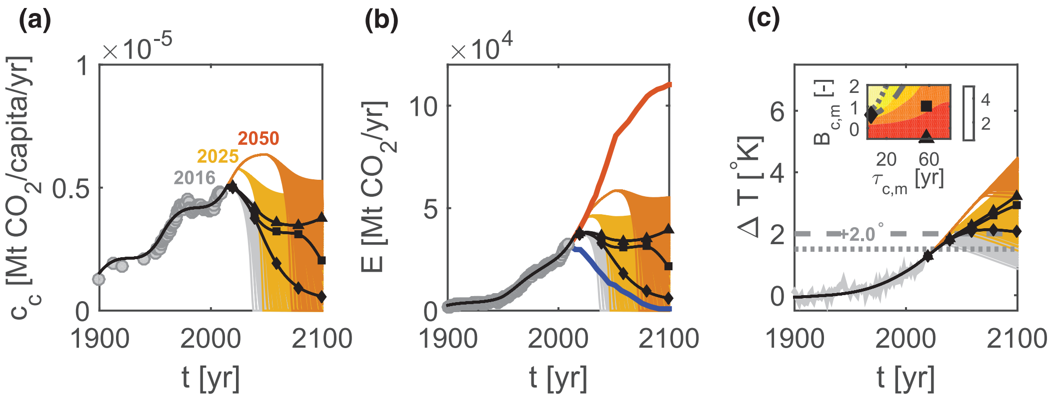

Figure 2. Delayed diffusion of climate-friendly innovations and implications for warming targets. Projected (a) per capita emissions c_c, (b) global emissions E, and (c) surface temperature anomaly ΔT for different mitigation scenarios and emission peaks $t_m = 2016$, 2025, and 2050 (gray, yellow, and orange lines, respectively). Three scenarios for $t_m = 2016$ are highlighted: an industrialization-like diffusion of renewable energies ($B_{c,m} = 1.05$, $\tau_{c,m} = 58$ years, squares in panels a–c), a faster-than-industrialization scenario ($B_{c,m} = 0.6$, $\tau_{c,m} = 6$ years, diamonds) and the failure of zero-carbon energy sources ($B_{c,m} = -0.5$, $\tau_{c,m} = 58$ years, triangles). The range of values for the model parameters $B_{c,m}$ and $\tau_{c,m}$ and the resulting temperature anomaly in 2100 (with $t_m = 2016$) are also illustrated in panel c (inset) together with the 1.5 and 2.0°C target limits (dashed and dotted lines, respectively).

present). However, a future stabilization of the world population (Figure 1c) can amplify such oscillatory behavior originating from c_c (Figure 1d).

When forced by established E scenarios (business-as-usual and halved-by-2050 [*Meinshausen et al*., 2009]), the resulting zero-dimensional model provides realistic CO_2 and temperature predictions (i.e., results within the range of uncertainty in existing coupled carbon-climate models that are spatially explicit, see Figures 1e and 1f and Appendix S1). The analyses next reveal how low-carbon emitting technologies must spread globally and efficiently to limit 21st century warming below 2°C. Consider the scenario where "peak" E is optimistically reached in 2016 and c_c follows similar punctuated dynamics as in the historically observed industrialization, but with drops instead of jumps (i.e., $\tau_{c,m} = \tau_c$ and $B_{c,m} = B_c$). The interplay between projected population growth and delayed innovation transfer causes nontrivial rebound effects jeopardizing the 2°C target (Figures 1f and 2). Given the need to provide an increasing number of people (now in billions) with energy access and accepting the impossibility of establishing control mechanisms to keep N at some desirable level, extreme reductions in c_c are required. Here, the feedback on N from adverse climatic conditions have not been explicitly considered though such feedbacks are routinely called for in studies of sustainability and collapses [*Motesharrei et al*., 2014]. In part, there are large uncertainties in prescribing such feedbacks given the multiple pathways and manifolds they operate on (e.g., health, water, agriculture and food security, war and conflict, etc.). Hence, the N projections here cover a wide range of scenarios (from super-exponential growth to decline), though any N-climate feedback that diminishes appreciably N means the "too late" phase has been crossed. As a consequence, to limit global warming below 2°C, the use of renewable energy sources and large-scale deployment of negative emissions technologies must spread with historically unprecedented minimal delays. The faster the diffusion of low-carbon emitting technologies, the lower the efforts required to decrease emissions. In particular we find that, for $\tau_{c,m} = 6$ years, a relative decrease of the per capita emission capacity of 60% will allow reaching the 2.0°C target by 2100. However, effective decisions to reduce E overriding characteristic timescales of technological spread need to be reached imminently to avoid rebounds and unacceptable warming (Figure 2). If a peak in E is not reached by 2030, reducing c_c may simply be "too little, too late." Furthermore, if N does not stabilize during this century [*Gerland et al*., 2014; *Warren*, 2015], an even greater innovation diffusion rate will be needed to avoid serious E rebounds and warming well above the target threshold (see Appendix S1).

4. Conclusions

Gambling on future technological innovations alone to reduce the anthropogenic CO_2 emissions [*Koningstein and Fork*, 2014] is risky and insufficient to avoid unacceptable warming. In fact, accelerating the spread of low-carbon emitting or green technologies is equally necessary to meet the warming targets established by the Paris agreement [*Hulme*, 2016]. If recent history offers any lessons, it is that diffusion and adoption of green technologies will face known and much discussed challenges. Our quantification of the delays historically associated with such challenges shows that a tenfold acceleration in the spread of green technologies is necessary to elicit some delay in the Doomsday clock [*The Bulletin of the Atomic Scientists' Science and Security Board*, 2016]

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