Detecting and Responding to Climate Change

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Abstract

The statistically significant demonstration of the dominant anthropogenic contribution to global warming has contributed significantly to the public acceptance of the reality of climate change. However, the separation between human induced climate change and natural climate variability on the regional scales of greatest relevance for human living conditions is inherently more difficult, Climate mitigation and adaptation policies must therefore necessarily be designed as the response to uncertain risks. Unfortunately, climate policy has stagnated in recent years through the preoccupation with the global financial crisis. Climate scientists can help overcome the current climate policy impasse through the creation of a new generation of simple, actor-based, system-dynamic models that demonstrate the close connection between the stabilization of the global financial system and effective climate policies. Examples are given of alternative stabilzation policies that can lead either to major recessions and unemployment or to stable economic growth supported by an accelerated decarbonization of the economy.

1 Introduction

The reality of human induced global warming is no longer seriously disputed. The world-wide acceptance today of the dangers of climate change represents a major transformation in public perceptions since the 1972 Report of the Club of Rome [Meadows et al, 1972] first drew broad attention to the finite resources, absorption capacity and vulnerability of our planet. Yet the overall societal and political response to the challenges of climate change, despite significant individual and regional initiatives, remains woefully inadequate. Can science help overcome the present disparity between understanding and responding to climate change?

It is perhaps useful to compare the past debate over the reality of human induced climate change to the present debate on how society should respond. In both cases scientists have strived to achieve a change in public perceptions, in the first case with respect to the impact of human activities on the future evoluton of the planet, in the second case with regard to the actions needed to mitigate the impact. Characteristic in both cases is the inherent inertia of ingrained public attitudes, and the need for special efforts to bring about a change. This is, of course, a subject that was always very much to the heart of Bert Bolin, who, among his many scientific achievements, was a leading innovator and pioneer in bridging the gap between science and society.

The breakthrough in the public acceptance of the reality of climate change came through the creation of the UN International Panel on Climate Change in 1988. This was a mojor diplomatic achievement of Bert Bolin, who then also became its first chairman, until 1997. An important supporting factor was the demonstration in the mid 1990s (Santer et al. (1994), Hegerl et al. (1996)), that the measured global warming since the beginning of industrialization could no longer be attributed with reasonable probality to natural variability. The computed significance level, based on the latest climate models. was estimated as less than 5%.

For scientists, this was not particularly exciting. The observed global warming of the order of 0.7^0C was consistent with the computed global warming due to the measured increase in the concentrations of CO_2 and other greenhouse gases. Whether or not this could be distinguished in the data from the natural climate variability, which could be inferred, prior to more realistic global climate models, only from relatively short instrumental time series and longer term treering and similar proxy data, appeared a rather irrelevant academic question. Sooner or later the anthropogenic signal was bound to rise above the natural variability noise. The reality of anthropogenic climate change followed from the physics of the radiation balance of the atmosphere, which had been understood in principle since Arrhenius's (1896) classic paper. Nevertheless, the first quantitive estimates of the signal-to-noise ratio of the observed warming produced a major boost in the public acceptance of global warming.

Can climate scientists bring about a similar boost in the public support of an effective policy response to the threat of climate change?

In the second part of this paper, I argue that climate scientists, in collaboration with economists, can provide important new perspectives on climate change policy in the context of the major financial and economic restructuring tasks facing all countries in the aftermath of the global financial crisis.

2 Detection and attribution

The estimate of the signal-to-noise ratio of climate change had became possible in the earlier nineteen-nineties through the development of coupled global-atmosphere-ocean climate models which were able to provide more realistic simulations of both the anthropogenic climate change signal and the longer term natural climate variability induced by shorter-term stochastic weather variability, Hasselmann (1976). To demonstrate a statistically significant human impact on climate it is not sufficient to detect only a climate change signal which exceeds the natural climate variability noise level at some statistical confidence level; one must also attribute the signal to human activity, i.e. demonstrate that the signal cannot be explained by some other external, non-human impact, such as a variation in solar activity, or volcanic eruptions. One will also wish in general to distinguish between different anthropogenic impacts, such as the emission of greenhouse gases as opposed to aerosols.

The standard detection-and-attribution approach is the optimal fingerprint method Hasselmann (1979, 1993). For a given set of time series $c_i(t), i = 1, 2, \ldots$ of observed climate variables (e.g. near-surface air temperatures, atmospheric vertical profile parameters, oceanic mixed layer temperatures, annual maximal or minimal sea-ice extent, etc.) one computes the theoretical response pattern $r_i^j(t)$ for a given climate forcing j. This is then compared with the observed response $\hat{r}_i(t)$. The predicted response is said to agree with the observed response at a given statistical confidence level if the deviation $r_i^j(t) - \hat{r}_i(t)$ between the predicted and observed response lies within the appropriate confidence ellipsoid of the natural variability noise $\tilde{r}_i(t)$.

The key feature of the fingerprint method is the weighting of the data such that the signal-to-noise ratio is maximized. This can be achieved either by using the non-weighted climate signal $r_i^j(t)$ and using a non-Euclidean metric, namely the inverse of the covariance matrix of the natural variability noise, when computing the root mean square deviation between the observed and predicted climate signal. Or, alternatively, one can retain the more familiar Euclidean metric in weighting the differences between signal and noise and weight instead the climate change signal. The signal pattern $r_i^j(t)$ is thereby replaced by a skewed *optimal fingerprint* pattern in which climate components associated with higher signal-to-noise ratios are weighted more heavily than components with lower signal-to-noise ratios.

In computing the transformation from the signal to the optimal fingerprint pattern, both the type of variable i and the time dependence t must be considered. For example, if one wishes to combine the last thirty-year trend of globally averaged near-surface atmospheric temperature with, say, the trend over the last 100 years of the surface pressure in Stockholm in joint climate change detection analysis, the former data would be characterized by a higher signal-to-noise ratio than the latter and would therefore receive a higher weight. To formalize this joint time-plus-variable dependence, it is convenient to discretize the time variable t and combine it with the climate-variable index i in a single composite index $k \equiv (i, t)$. The net signal pattern can then be represented as a vector $\mathbf{g}^j = (g_k)^j \equiv r_i^j(t)$.

In this notation, the optimal fingerprint pattern $\mathbf{f}^j = (f_k)^j$ is given by

$$\mathbf{f}^j = \mathbf{C}^{-1}\mathbf{g}^j$$

where

$$\mathbf{C} \equiv C_{kl} = < n_k n_l >$$

denotes the covariance matrix of the natural variability noise $n_k \equiv \tilde{r}_i^j(t)$.

If two or more competing forcings are compared, the relative significance of the computed climate response signals can be compared in the plane or higher-dimensional space spanned by the two or more associated fingerprint patterns. Figure 1, from Barnett et al. (1999), illustrates the application of the optimal fingerprint method to discriminate between the climate response to two different anthropogenic forcings: greenhouse gas emissions alone (G), and a combination of greenhouse gas and sulfate aerosol emissions (GS). Various simulations using models of the Hadley Centre, the Max Planck Institute and the Geophysical Fluid Dynamics Laboratory are shown, using the fingerprint transformations computed with the Max Planck model (left panel) and the Hadley Centre model (right panel). Most of the GS simulations lie within the 95% confidence ellipses of the natural variability, while the G simulations largely lie outside the ellipse. Thus the detection and attribution analysis supports the hypothesis that the overstimation of the greenhouse warming by many models was due to the neglect of the (regionally dependent) cooling effect of sulfate aerosols.

The above example, as most of the early detection and attribution analyses, was based on near-surface atmospheric temperature data,

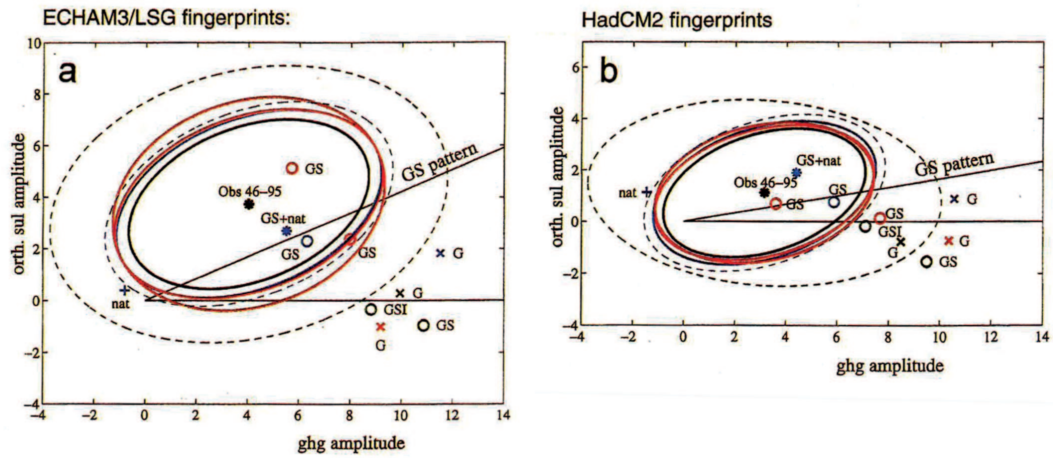

Figure 1: *Computed climate response signals to greenhouse gas emissions alone (G) and a combination of greenhouse gas and sulfate aerosol emissions (GS), with associated 95% confidence ellipses, for simulations of the Max Planck Institute for Meteorology (left) and the Hadley Centre (right). Reproduced from Barnett et al. (1999))*

for which there exist relatively long time series and acceptable global coverage. However, the optimal fingerprint approach has since been extended to a wide variety of data sets, including upper-layer ocean temperature, Arctic sea-ice extent, rainfall patterns, surface humidity, atmospheric moisture, continental river run-off and (Figure 2) atmospheric vertical temperature (see detailed review by Santer (2010)).

This has provided exceptionally broad confirmation of the major anthropogenic contribution to recent climate change, as expressed in the increasing confidence in consecutive IPCC assessments, from the first 1995 statement that ”The balance of evidence suggests a discernible human influence on global climate” to the latest 2007 conclusion that ”Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations”. Nevertheless, the detection and attribution analysis is necessarily strongly dependent on model computations of the climate response to external forcing and the internal climate variability, as well as on data records which provide only indirect proxy information or, in the case of instrumental data, are of limited duration. It will thus always be associated with a certain residual level uncertainty.

The uncertainties increase if the detection and attribution method is applied to the impacts of climate change. The statistically robust conclusion that human activities have produced an observable change

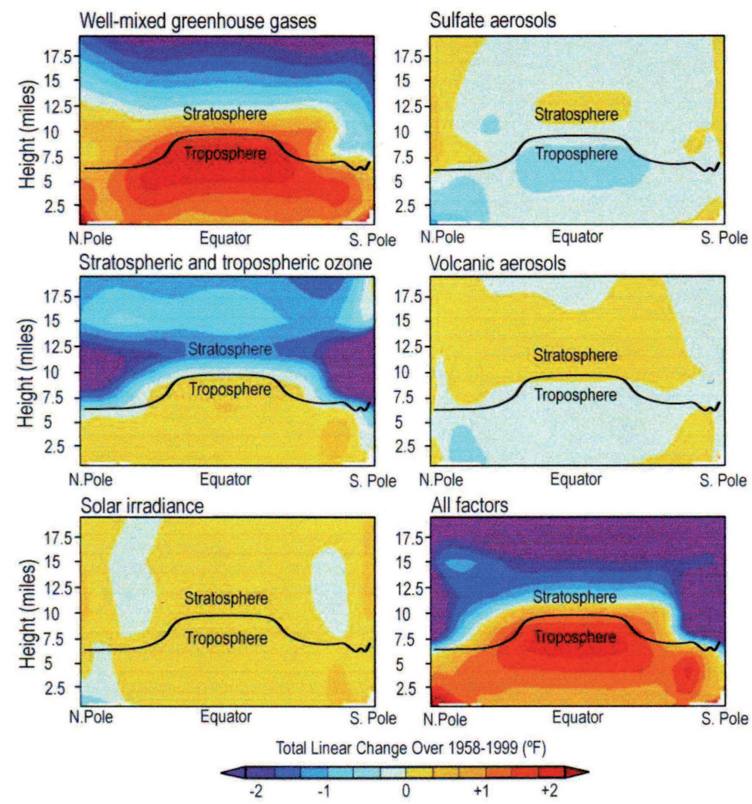

Figure 2: *Vertical profiles of temperature change for five different forcings, and their sum (bottom right). The computed total change agrees well with observations. The decomposition confirms that most of the observed change is due to greenhouse gas forcing (from Karl et al. (2009))*

in climate rested strongly on global or large-scale regionally averaged data. The impact of anthropogenic climate change on human activities, however, is dominated by smaller scale or shorter-term processes, such as changes in the frequencies and intensities of storms, floods and droughts, local water availability, or local sea level rise. The demonstration that observed changes on these scales are indeed attributable to human activities is difficult to achieve with acceptable statistical significant because of the limited spatial resolution of global climate models and the relatively short period of available instrumental data.

Nevertheless, changes in atmospheric circulation patterns, with attendant changes in the frequencies of extreme events, must be expected for a warmer climate, and are predicted by models. There is mounting evidence that the increase in recent severe storms, major floods

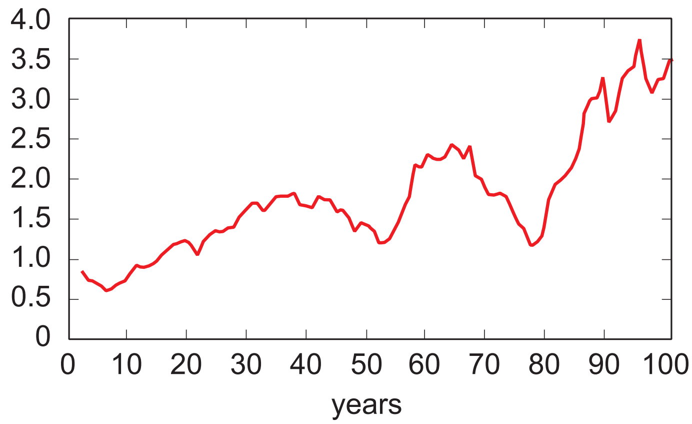

Figure 3: *Ten-year averages of the number of monthly-mean heat records at 17 stations worldwide (corresponding to a total of 17 x 12 = 204 heat records)*

and extensive droughts highlighted by the media can no longer be explained, in their accumulation, by natural variability alone.

Figure 3, from Coumou and Rahmstorf (2012), shows, for just one example, the computed temporal distribution of monthly-mean temperature records for each month of the year, determined over a period of a hundred years at 17 stations worldwide. In the absence of an anthropogenically induced trend or centenial-scale natural variability, the temporal distribution of the total number 17 x 12 = 204 of heat records would lie randomly distributed about a horizontal line. The observed upwards trend is strongly suggestive of an anthropogenic influence, although centenial-scale natural variability (as in all such investigations) cannot be ruled out.

Figure 4 summarizes qualitatively the uncertainties encountered in the detection and attribution of anthropogenic climate change. The curves have been extrapolated from the detection and attribution of present climate change into the future. It is the future warming, of course, estimated as 3^0 C or more within this century, that concerns society more than the present global warming of 0.7^0 C. The predicted warming – of comparable magnitude to the warming since the last ice age, but occurring two orders of magnitude more rapidly – is unprecedented in the history of mankind.

However, the uncertainties increase significantly as one projects further into the future. This due not only to the growing divergence between the predictions of different climate models, but also to significant differences between alternative assumed projections of future greenhouse gas emissions, IPPC, Working Groups 1, 2 and 3 (2007). From the socio-economic planer's perspective, the uncertainties must

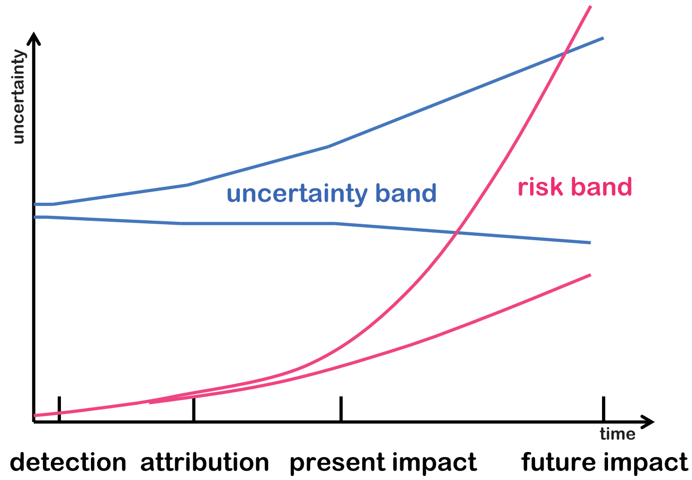

Figure 4: *Qualitative distribution of uncertainties associated with the detection, attribution, prediction and impact of climate change, with attendant widening risks.*

be addressed as risk assessments. The challenge of the policymaker is thus not to respond to a well defined predicted future state, or to wait (in vain) until science has removed all uncertainties, but rather to develop appropriate policies to deal with a spectrum of possible evolution trajectories, with unavoidable uncertainties and risks that must be assessed in relation to overall policy objectives.

3 Responding to climate change

Scientists have been warming of global warming ever since a continuous monitering station, installed by David Keeling in 1957 (with the support, among others, of Bert Bolin) on Mauna Loa, started recording a monotonic increase in annual mean atmospheric CO_2 concentrations. The predictions by scientists of the resultant future global warming have not changed significantly over the last fifty years. But the political response has been slow and inadequate. Climate scientists have attempted to accelerate the poliical process by collaborating with economists in constructing integrated assessment models, in which alternative paths for achieving a low-carbon global economy have been explored, IPCC, Working Group 3 (2007). However, these analyses have had relatively little political impact. This has been particularly evident since the financial crisis of 2008. The failure of the economic profession to predict the crisis has unfortunately undermined the credibility of the economic models on which most of the integrated assessment studies were based.

Thus there is a need for scientists to construct a new generation of integrated assessment models based on more realistic representations of the socio-economic-financial system. More effective means must also be developed for communicating with stakeholders and decision makers. This requires the construction of simpler, more easily understandable models that address the issues of the current political debate (see the review of Giupponi et al. (2012) and the accompanying papers published in the Thematic Issue of the same journal).

A basic difficulty of this approach, however, is that there exists today no consensus within the economic community on how the socio-economic-political system actually works. The prevalent pre-2008 picture of a basically stable system, that adjusts always to an equilibrium growth path if left to the shock-absorbing forces of the free market, has not survived the financial crisis. Widespread agreement exists only that Adam Smith's single utility-optimizing "invisible hand" needs to be replaced by a more realistic ensemble of socio-economic-political actors, whose competing strategies jointly determine the evolution of the system. The complex high-dimensional mathematical general equilibrium models of the main-stream economic school have accordingly been replaced in the political arena – since alternative computer models were not yet available – by mental models based on intuitive concepts of how the diverse actor strategies actually play out in the real socio-economic-financial system.

Unfortunately, the preoccupation with the global financial crisis and its associated repurcusions such as the Euro crisis have focussed the political debate on these immediate issues, sidetracking the equally important long-term problem of climate change. However, as we show below, the two problems are in fact intimately interconnected and need to be addressed in conjunction.

By translating the various competing mental pictures of the socio-economic-political system that dominate the current political debate into quantitative, easily comprehensible actor-based, system-dynamic models, scientists can move the frequently ideological controversies over the optimal regulation of the global socio-economic system into the more objective arena of rational analysis. A clarification of the basic system dynamics would open new perspectives on the resolution of the present instabilities besetting the socio-economic-financial system, identifying in the process new paths to achieving the transformation to a decarbonized economy.

A new generation of integrated assessment models would need to include the following features:

- A number of different actors (firms, workers, consumers, governments, banks, etc.) pursuing individual goals. In contrast to the single stable equilibrium of the main-stream efficient market paradigm, interactions between several competing players can lead to a wide variety of stable or unstable trajectories, including multiple quasi-equilibria, exponential growth, catastrophic collapse, and continuous chaotic evolution. A better understanding of the associated feedback processes is a necessary condition for the application of effective economic regulation measures.

• An explicit representation of the basic conflicts of interest between individual and public goals. These arise both at the level of individual actors and at the international level of countries.

• A realistic representation of the interaction of the financial system with the real economy.

• A generalization of the concept of human value or happiness, including other factors besides the standard economic measure of GDP.

The purpose of such a multi-actor model system would not necessarily be to advocate a particular preferred policy, but rather to provide a 'canvas' Dietz et al. (2007) for painting alternative pictures of the socio-economic-political system as input for a quantitative analysis and discussion leading, hopefully, to a consensus. As example, we present in the following a series of model simulations summarizing various views of the interrelation between the tasks of stabilizing the financial system while decarbonizing also the economy.

A globally integrated green-growth model

The challenge of achieving a transition to a low-carbon global economic system is summarized in Figure 5 in terms of the wedge Pacala and Socolow (2004) separating a typical "Business-as Usual" path of greenhouse-gas emissions (expressed in terms of CO_2 equivalent gigatonnes of carbon, cf. IPPC, Working Groups 1, 2 and 3 (2007), and a "sustainability" path that would restrict global greenhouse warming to less than 2^0C. The 2^0C limit, proposed by scientists as a realistic value in order to avoid "dangerous climate change", has been accepted as global mitigation goal (although not accompanied by matching commitments) at the 15^{th} session of the Conference of Parties to the UN Framework Convention on Climate Change (UNFCCC) in Copenhagen in December 2009.

Also shown are a possible combination of technologies for closing the gap, beginning with the lowest (essentially zero or even negative) cost option of more efficient energy use and ending with the (currently) more expensive but essentially unlimited option of solar energy.

There exists widespread agreement among experts that, techni-

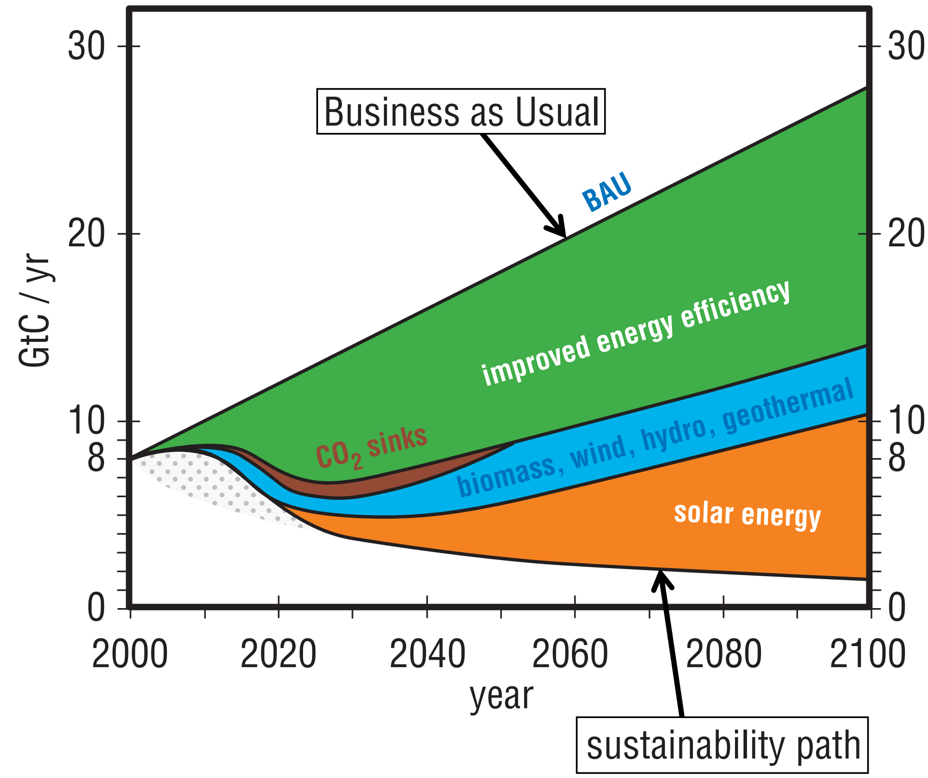

Figure 5: *Closing the wedge between a typical Business-as-Usual (BAU) greenhouse gas emissions path and a sustainability path that remains below the* 2^0C *global warming guard rail. Renewable energy technologies are ordered with respect to present costs. Solar energy is the largest, in practice unlimited, resource, followed by wind power.*

cally, the global energy system can be completely decarbonized during this century without exceeding the 2^0C warming limit by applying renewable-energy technologies that are available already today. It is also generally accepted that the global costs of avoiding dangerous climate change are significantly lower than the potential costs, with attendant incalculable risks, incurred by unmitigated global warming, Stern (2007).

The consensus view is summarized in Figure 6, which shows the growth of GDP computed for two simulations R-BAU and R-GREEN corresponding to a non-mitigation (business-as-usual, BAU) and a mitigation scenario that remains below the 2^0C global warming limit, respectively (GDP, y, is represented here and in the following in arbitrary currency units "\$"/year). The GDP curves are computed using a modified version of the Multi-Actor Dynamic Integrated Assessment

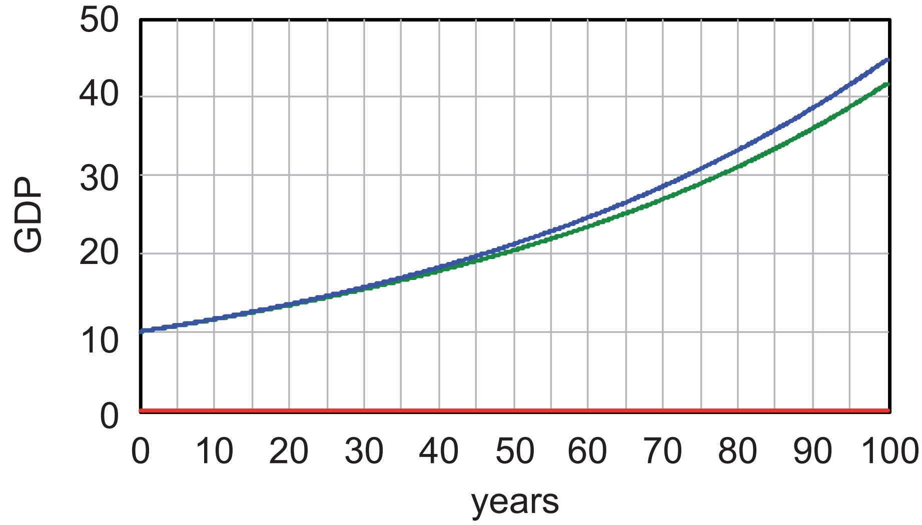

Figure 6: *Computed growth of GDP for a business-as-usual scenario (blue) and a reduced-emission scenario (green) for which the global warming remains below 2^{0}C. Mitigation measures incur a growth delay over a period of 100 years of only a few years.*

Model System (MADIAMS), Weber and Hasselmann (2005), Hasselmann and Kovalevsky (2012), Hasselmann and Voinov (2011).[1] The results are consistent with other investigations (e.g. Azar and Schneider (2002), Stern (2007), IPPC, Working Groups 1, 2 and 3 (2007)), all of which conclude that the slightly higher short-term costs of renewable energy are negligible compared with the longer-term climate-damage costs of the BAU scenario. The loss of GDP incurred by mitigation policies incurs an acceptable delay of economic growth over a period of 100 years of only a few years.

The simulations in the present case were based on a simple system-dynamics representation of the real economy in terms of the subdivision of the output y of the economy into three components y_r, y_k and y_g representing the production of fossil-energy-based capital k, renewable-energy-based capital r, and consumer goods and services, g (Figure 7). The input flows are offset by outflows representing capital depreciation and the consumption of consumer goods and services. The input production streams y_k, y_r provide no direct contribution to the production of consumer goods and services – the ultimate purpose of the economy – but generate rather the renewable and conventional capital components r, k that are needed as input to the

[1]The VENSIM code of the MADIAMS model system can be downloaded from the website of the Global Climate Forum, http://www.globalclimateforum.org/.

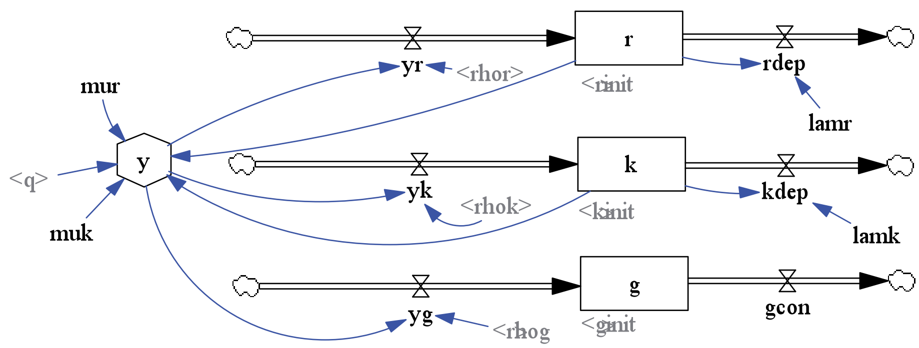

Figure 7: *Vensim-software sketch (cf. http://www.vensim.com) of the stocks (boxes) and flows (choke valves – or hour glasses) of a simple real-economy model (see text). Details of the various inputs to the stocks and flows are not shown.*

production function itself: $y = y(r, k)$. We have assumed the simple form $y = \mu_r r + \mu_k k$, where μ_k is a constant and μ_r is a function that gradually increases at a rate proportional to y_r, simulating the learning-by-doing effect for a new technology.

The term "capital" is used here in its widest form, including physical and human capital (education, job experience, etc.) as well as institutions (legal and administrative system, ethics, national constitution, governmental structure, etc.). The formal division of capital into conventional-energy and renewable-energy dependent components is based on an estimate of the relevant contributions of these two energy input components into the production function, under the basic hypothesis that the creation of all outputs of the economy involve ultimately some form of energy input.

In the simulation R-BAU, the relevant output fractions of total production were set at the fixed values $\rho_r = 0, \rho_k = 0.65, \rho_g = 0.35$, while in the simulation R-GREEN, the fraction ρ_r was gradually increased relative to the fraction ρ_k, while retaining the same fraction $\rho_g = 0.35$ for the production of consumer goods and services (Figure 8). The impact of the two scenarios on climate (expressed in terms of the global mean temperature increase T) and human welfare w is shown in Figure 9. The temperature increase was computed using a simplified version of the nonlinear impulse response climate model NICCS (Hooss et al. (2001)) from the CO_2 emissions associated with the production y_k in the fossil-energy-based sector.

The representation of the joint impact of economic growth and climate change on human "welfare" necessarily involves a subjective value assessment. Generally accepted is only that welfare depends

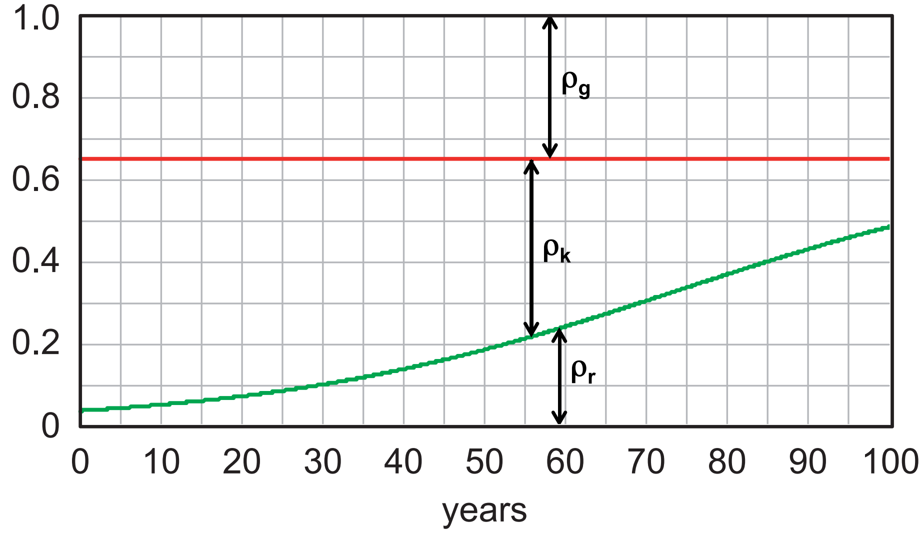

Figure 8: *Evolution of production-distribution factors for the simulations R-BAU ($\rho_r = 0, \rho_k = 0.65, \rho_g = 0.35$) and R-GREEN (green curve, with $\rho_g =$ 0.35 and ρ_r and ρ_k monotonically inceasing and decreasing, respectively.).*

not only on GDP (y – or, more appropriately, the production y_g of consumer goods and services) but also on many other factors, such as health insurance, unemployment levels, job security, crime level, income inequalities, pension guarantees, and – of particular relevance in the present context – the state of the environment.

Without entering into the extensive discussion in the literature of the welfare concept, we set in our models for illustrative purposes simply

$$w = y_g \, q \, \exp(-0.1T^2) \tag{1}$$

where q denotes the employment level and T denotes the global mean temperature increase. In our first simulations R-BAU and R-GREEN, full employment was assumed, so that the welfare values shown in Figure 9 depend only on y_g and T.

The pronounced loss in welfare of the BAU scenario compared to the green scenario could conceivably have been exaggerated in our example by exceptionally low welfare values of the chosen BAU scenario. That this is not the case is demonstrated in Figure 10, which compares the simulation R-BAU ($\rho_k = 0.35$) with three further simulations R-BAU-1,2,3 ($\rho_k = 0.25, 0.45, 0.55$). The reference BAU scenario is seen to be characterized by the highest relative welfare values.

The reproduction of these basically well-known results with a simple system-dynamics model of the real economy emphasizes two important points. First, the conclusions are strongly dependent on un-

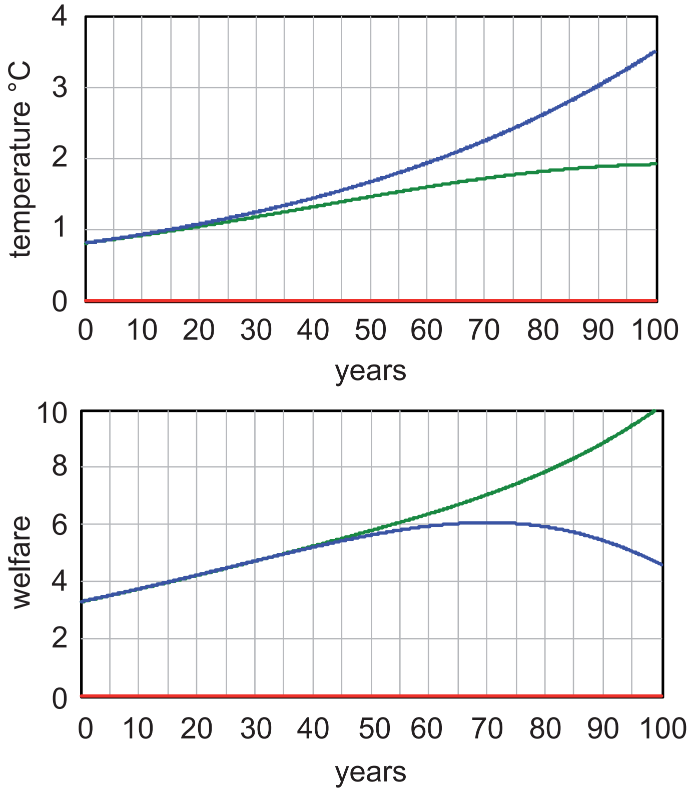

Figure 9: *Impact of the two scenarios R-BAU (blue) and R-GREEN (green) on global mean temperature (upper panel) and welfare (lower panel).*

avoidable uncertainties and value assumptions. These follow from the uncertainties of climate predictions and future economic growth, and the necessarily subjective nature of the welfare concept. The latter depends, in addition to the factors mentioned, on the weighting of future welfare values relative to present values. We have not attempted to represent this through a discount factor, a long-standing subject of debate (see, for example, Nordhaus (1997), Hasselmann (1999)) and the more recent controversy (Tol and G.Yohe (2006), Nordhaus (2007)) over the low discount factor used in the Stern review, Stern (2007). The root of the controversy lies ultimately in the conflict between private and public goals: the short time scales of private investors seeking a rapid return on investment are incompatible with the longer time horizon of governments concerned with preserving a habitable planet for future generations. The task of policy-makers is to balance these two objectives, both of which have their legitimacy.

Secondly, the evolution of the economy is governed by the strategies of the economic actors that determine the distribution of produc-

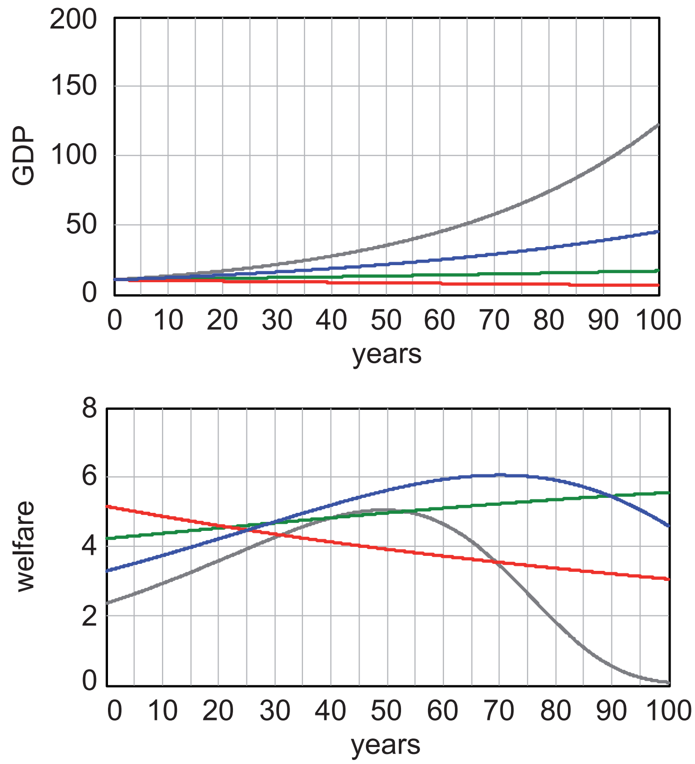

Figure 10: *Evolution of GDP (upper panel) and welfare (lower panel) for four BAU scenarios corresponding to* $\rho_k = 0.25, 0.35, 0.45, 0.55$, *with* $\rho_r = 0$ *in all cases. The reference scenario R-BAU (blue), with* $\rho_k = 0.35$, *yields the highest welfare values.*

tion between the three output streams y_r, y_k, and y_g. In contrast to the general consensus on the technical feasibility and affordability of decarbonization, there exists no widespread agreement on the most effective policies for creating the necessary incentives for economic actors to engage in the green transformation. Instead, individual actor behaviour can produce major instabilities, as exemplified by the recent financial crisis, and discussed further below. This underlines that the goal of decarbonization is closely interconnected to the task of stabilizing the coupled economic-financial system.

To investigate the role of actor behaviour, our real-economy model needs to be extended to include the financial system (Figure 11). The evolution of the complete model is governed by the strategies of five types of economic actors: a firm, a household, a government, an investor, and a central bank. To distinguish between the investment streams in carbon-based and renewable-based capital stocks, each firm and investor is further subdivided into two actors, yielding a total of

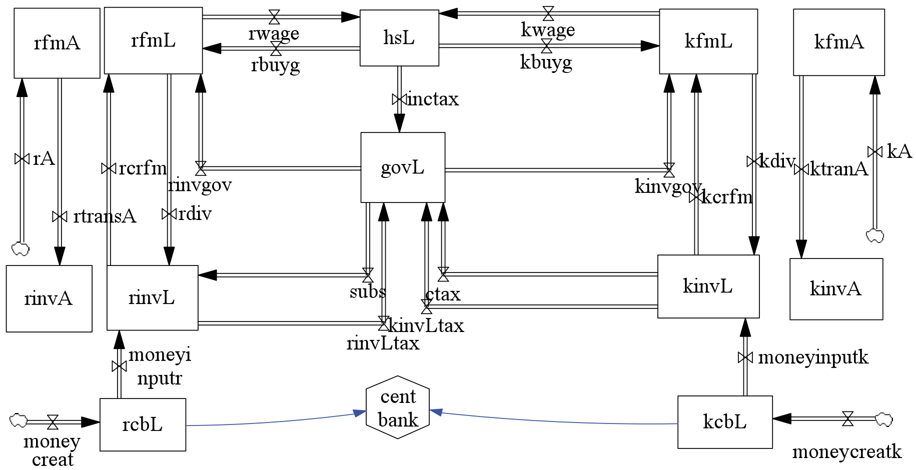

Figure 11: *Vensim-model sketch of the financial system sector coupled to the real-economy model of Figure 7. Money stocks and flows assigned to firms and investors are separated into renewable-energy-related liquidity and assets (left) and fossil-energy-related liquidity and assets (right). Details of the various inputs to the stocks and flows are not shown.*

seven formally independent actors.

The complete model consists then of twelve state variables: three for the real economy (conventional and renewable based capital r, k and consumer goods and services g), and nine for the financial sector: seven representing the actor liquidities (hsL, govL, kinvL, rinvL, kfmL, rfmL, cbL) plus two state variables for the assets (kinvA, rinvA) owned by investors. It is assumed that, with the exception of investors, who own the capital assets of the firms in which they have invested, the wealth of all actors is expressed solely in terms of liquidity. The role of the central bank is to create new money in response to the expansion of the economy. This is achieved by satisfying the money demand of investors, which act indirectly as the originators of new money by providing credit to firms.

The evolution of the financial system is governed by the money transfers between the nine state variables. The money flows, in turn, depend on a number of actor-dependent "transfer" parameters, namely: the wages negotiated between firms and wage-earners (households), the fraction of wages saved by households as opposed to the purchase of consumer goods, the purchase of capital assets from firms by investors, the dividends investors receive from firms, the prices of consumer goods and capital assets, the income tax and carbon taxes imposed by the government, the recirculation of the tax income to firms in the form of investments and subsidies, and – a particularly important variable that enters as a factor in all transfers involving households as well as in all production variables – the employment level.

Our model, despite its numerous interconnections, is clearly a highly idealized representation of the real socio-economic system. However, it already captures many of the actor-dependent dynamical features observed in the real socio-economic-financial system. These can be either stabilizing or destabilizing, as opposed to the enherent stability assumed in main-stream general equilibrium models. For the following, the details of the model (specified, for example, in alternative realizations in Weber and Hasselmann (2005) and Hasselmann and Kovalevsky (2012)) are irrelevant. The emphasis here is on the model's basic dynamic structure and the controlling role of actor behaviour. The dynamical properties of different model realizations can be classified with respect to the assumed actor responses to market signals.

Supply-driven systems

The simulations R-BAU, R-GREEN and R-BAU-1,2,3 were concerned only with the real economy, but were nevertheless carried out for intercomparison purposes using the full coupled model. The financial sector was effectively decoupled from the real economy through the market-clearing assumption that the outputs r, k and g of the real economy were immediately purchased by the actors through appropriate price adjustments. Thus, it was sufficient to specify only the parameters μ_r, μ_k and ρ_r, ρ_k, ρ_g governing the production in the real-economy sector. In the following, we consider first alternative realizations of the financial sector for a given supply-driven, market-clearing realization of the real economic sector. Subsequently, we investigate the more general case of a feedback of the financial sector on the real economy through supply-demand interactions, including variations in the employment level.

Further conclusions can be drawn for supply-driven systems if (as in our examples R-BAU, R-BAU-1,2,3) the systems are stable and linear. The general solution in our cases consisted of a superposition of two eigensolutions: an exponentially growing solution $(r, k, g) = (0, k_1, g_1) \exp(\gamma_1 t)$ and an expontially decaying solution $(r, k, g) = (0, 0, g_2) \exp(-\gamma_2 t)$, with postive constants $k_1, g_1, \gamma_1, g_2, \gamma_2$. (There exist only two eigensolutions, since the three state variables r, k and g are linearly dependent through the side condition $\rho_r + \rho_k + \rho_g = 1$ underlying the growth parameters ρ_r, ρ_k and ρ_g.) The exponentially growing solution represents a stable attractor (an "equilibrium" in standard economic terminology).

The single equilibrium solution for the economic sector can be as-

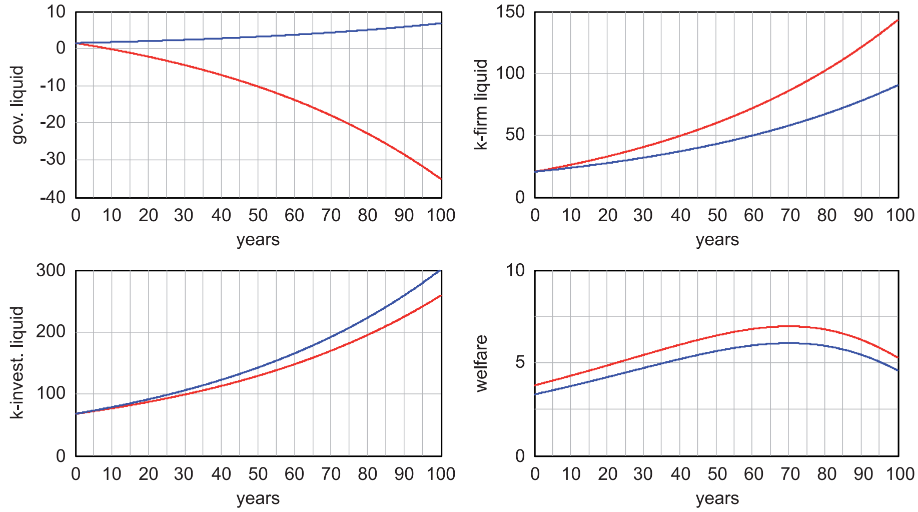

Figure 12: *Alternative evolutions of the financial sector of the model MADIAMS for the same evolution R-BAU of the real-economy sector. The scenario RF-BAU-BAL (blue) corresponds to balanced wealth growth of all economic actors commensurate with real eonomic growth, while the government-deficit scenario RF-BAU-DEF (red) yields higher but non-sustainable values of household welfare and firm liquidity, at the cost of increasing government deficits.*

sociated with an ensemble of possible solutions for the financial sector. Thus the evolution of the individual wealth components, in contrast to GDP, depends on the specific representation of the financial sector. This is illustrated in Figure 12, which compares two alternative solutions of the financial sector for the same solution R-BAU of the economic sector.

The first solution RF-BAU-BAL represents an example of a balanced financial system, characterized by a common exponential growth $\sim \exp(\gamma_1 t)$ of all variables of the financial sector, in concordance with the growth of the real economy. The second example RF-BAU-DEF represents an unbalanced system driven by a deficit government budget. The government debt is assumed to be financed by investors, and is spent by governments on orders for firms (the role of governments in redistributing wealth between different income groups is not resolved in our highly aggregated model). The firms, in turn, partially transfer the enhanced income to households in the form of higher wages. The deficit-budget case also yields an asymptotic exponential growth rate of all financial-sector variables $\sim \exp(\gamma_1 t)$, with the same common exponential factor, but in this case with a negative amplitude for the goverment. (The remaining eleven eigenvectors of the system consist of the exponentially decaying component $\sim \exp(-\lambda_2 t)$ mentioned above and ten constant components). Interest payments by the government are not represented as a separate money stream, since, for exponential growth, they enter simply as a factor modifying the credit uptake.

It is assumed that the additional credit supplied by investors to governments in the second example is not balanced by an additional money uptake from the central bank. Thus, the total wealth of the system is the same in both the balanced-budget and deficit-budget case. The welfare, as defined in Eq.(1), also remains unchanged, as the total production, the distribution of production and the assumption of full employment, remain the same. This is, of course, unrealistic in view of the increased household income in the deficit-budget case. It follows formally because, for a closed economy with a given level of production of consumer goods and services, the increased household income can lead only to an increased level of household savings (liquidity), which is not reflected in our welfare definition (1). We assume therefore in the deficti-budget case, more realistically, that the increased household income produces an increased consumption level $y_g^{tot} = y_g + y_g^{imp}$ through the purchase y_g^{imp} of imports from a foreign economy. This can be expressed by replacing y_g in Eq.(1) by y_g^{tot}, yielding the welfare curve shown in Figure 12 (bottom right).

The enhanced welfare of the deficit model is sustainable only as long as investors are willing to accept an increasing outstanding government debt, and the foreign economy maintains the trade imbalance. At some point, however, the investors will balk, and an attempt will be made to adjust the economy to the balanced-growth path of the scenario RF-BAU-BAL. Views on the best policy for achieving the transformation differ, depending on the assumed actor response.

If one adheres to the traditional main stream paradigm of an inherently stable economic system, the recipe is straightforward: one simply adusts the government expenditure and tax income such that they match, and the economy will automatically adjust to the balanced-budget growth path RF-BAU-BAL. This is shown in the simulation RF-BAU-SAV (Figure 13, blue curves SAV). The budget corrections were applied twenty years after the begin of the deficit growth path, with an assumed adjustment time constant of three years. The welfare level falls back to the reference BAU curve, as intended, without major repurcussions for the economy.

Unstable supply-and-demand-driven systems

This is not, however, what is typically experienced. Austerity policies in most cases lead to major recessions and unemployment (as observed

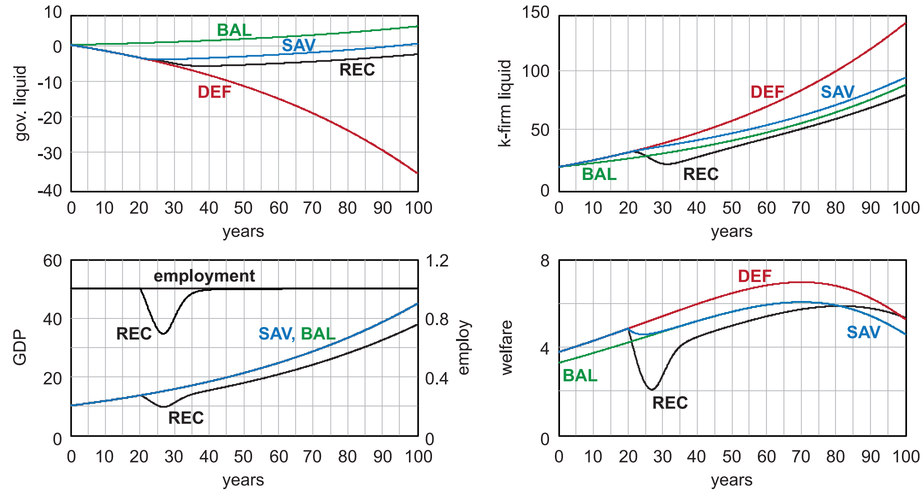

Figure 13: *Alternative predictions of the impact of strict saving measures to adjust the deficit-budget evolution path RF-BAU-DEF (red curves DEF) to the balanced-budget growth path RF-BAU-BAL (green curves BAL). The simulation RF-BAU-SAV (blue curves SAV) assumes a monotonic relaxation to the balance-budget path, while the simulation RF-BAU-REC (black curves REC) predicts a severe recession with major unemployment.*

in the southern European countries in the present Euro crisis). To reproduce these alternative outcomes (Figure 13, simulation RF-BAU-REC, black curves REC), the model needs to be generalized to include unstable actor responses to market signals.

The difference between the efficient-market paradigm of the simulation RF-BAU-SAV and the instabilities of the simulation RF-BAU-REC can be summarized in terms of the relation between the basic economic variables supply, demand and price for a single-good economy. In introductory macro-economic books, this is normally represented by the familiar diagonal-cross diagram demonstrating that the variables adjust always to a unique equilibrium. This is not necessarily the case, however, but depends critically on the assumed actor behaviour.

Consider, for example, the impact of an externally introduced small increase in the price of the good. Standard economic theory states that this results in a decrease in demand, to which suppliers respond by reducing the price, re-establishing the equilibrium. However, in the case of asset markets, speculative herding can produce the opposite response: anticipating rising prices, investors buy more assets, generating further price increases. The resultant unstable *reflexivity* Soros (2008) feedback of the actions of the market participants on the market values themselves is finally brought to an end and collapses through some nonlinear process, such as the panic response of investors beyond some price level.

Another case, more closely related to the present sovereign-debt example, is the creation of unstable business cycles through fluctuations in demand. Instead of reducing prices in response to falling demand, thereby stimulating a stabilizing increase in demand, firms may prefer to lay off workers. This further reduces demand, creating an unstable feedback cycle. Depending on further feedbacks, such as the relation between unemployment and wages, the instability can result in a relatively mild business cycle or a major recession.

Other instability mechanisms include the explosive proliferation of recent innovative financial products, such as credit default swaps (CDSs) and collaterized debt obligations (CDOs). Although claimed by their proponents to enhance stability by distributing risk, the ability to trade-off risk in fact encouraged investors to accept risks that they would otherwise not have engaged in. The resulting systemic instability has been belatedly recognized as an essential factor contributing to the global financial crisis.

The dynamics of boom-and-bust events produced by herding behaviour and the impact of business cycles on long-term economic growth have been investigated in the context of climate change mitigation policies in Hasselmann and Kovalevsky (2012). In the following, we apply the feedback dynamics of business cycles to the example of sovereign debt. Similar actor-based, system-dynamic models can be constructed to investigate other instabilities of the coupled economic-financial system, enabling a rational discussion of their resolution within the framework of an effective climate mitigation policy.

We assume in our example that the response of firms to government policies seeking to balance the budget (by reducing, for example, the wages of government employees, or postponing infra-structure investments) is not to lower prices in response to the decreased demand, but rather to reduce the supply by laying off workers. This further decreases demand, leading to an unstable positive feedback cycle. The exponential collapse of the economy is arrested in our model through the reduction of wages to a level at which firms again become willing to employ workers.

The impact of the reduced employment level q enters linearly in the overall production y, but quadratically in our assumed expression (1) for the welfare w– through the linear dependence of w on y and, additionally, on q directly. This results in a pronounced decrease in welfare (Figure 13, bottom right), which persists until it is finally compensated by the reduced climate warming associated with the reduced

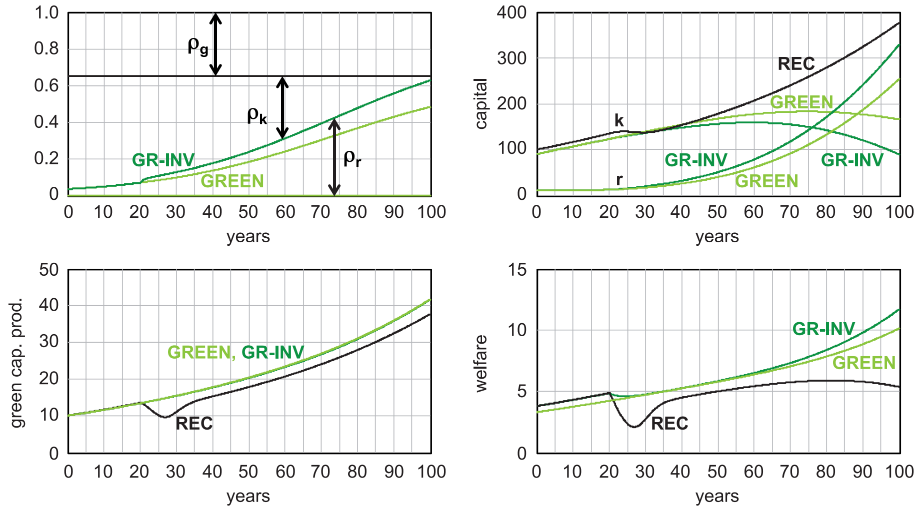

Figure 14: *Interrelation between decarbonization and stabilization of the financial markets. Simulation RF-GREEN-INV (dark green curves GR-INV) shows the impact of government savings measures accompanied by enhanced Keynesian investments in renewable energy. Simulation RF-BAU-REC (black curves REC) shows the impact of savings measures alone, leading to a recession. Also shown is the original decoupled real-economy decarbonization simulation R-GREEN (light green curves GREEN)*

CO_2 emissions of the depressed economy.

The rise in unemployment can be avoided if the necessary reduction of the workforce in the sector of consumer goods and services is compensated by the hiring of workers in a new production sector. An obvious candidate is the accelerated expansion of renewable energy technology. Figure 14 (green curves) shows the results for the simulation RF-GREEN-INV, in which the fraction ρ_r of total production invested in renewable energy capital is increased relative to the fraction assumed in the earlier greening simulation R-GREEN (Figures 8, 9). The increase in ρ_r is introduced after $t = 20$ years, coincident with the budget-balancing reduction in government transfers to the fossil-capital sector of the economy, which is applied as before.

The initial decrease in welfare is minor, and comparable with the decrease computed in the previous (unrealistically optimistic) simulation RF-BAU-SAV (Figure 13). Despite the shift of investments from consumption goods to green technology, the resultant welfare values lie very close to the R-GREEN curve in the medium term, and exceed these in the long term.

4 Conclusions

Extensive research following initial estimates of the signal-to-noise ratio in the early nineteen-nineties has today clearly established the dominance of human influence over natural climate variability in observed global warming data. However, this applies to the global scale; to what extent the observed increase in extreme events on regional scales, such as storms, droughts or heat waves, can be clearly attributed to human influence rather than decadal scale natural variability remains in many cases an open question. Nevertheless, climate models predict significant anthropogenic climate change also on these scales. Since these are the climate change impacts that are most relevant for human living conditions, society cannot afford to wait until the anthropogenic signal has clearly risen above the natural variability noise also on these scales, but must develop mitigation policies in anticipation of the major future impacts predicted by climate models in the event of unmitigated business-as-usual growth.

To support policy-makers, climate scientists need to collaborate with economists in producing realistic coupled climate-socio-economic models that are able to investigate the impact of alternative climate policies. Unfortunately, climate policy has stagnated in recent years through the preoccupation with the financial crisis. To overcome this impasse, the models need to reproduce both the instabilities that led to the financial crisis and the interactions with the climate system.

We have presented a simple actor-based, system-dynamic model system that satisifies these criteria. None of the concepts we have investigated are new. But the political debate on the resolution of the global financial crisis, with its more regional dislocations such as imbalances within the Euro region, has lacked hitherto a translation into simple, easily understandable simulation models. These are necessary not only for the verification or falsification of competing concepts against data, but at a more fundamental level already for testing the internal consistency of the conclusions drawn from the mental models. And they are needed to expand the present discussion focussing on the financial crisis to the important longer term goal of transforming the present global economy into a stable, carbon-free system. The greening of the global economy requires major long-term investments. These will be forthcoming only if investors have confidence in the stability of the system in which they are investing.

We have undertaken a first step to close the gap between mental models and quantitative computer simulations. Our translation of familiar concepts of the current socio-economic debate into simple actor-based, system-dynamic simulation models provides a tool for investigating the (often non-trivial stocks-and-flows) implications of the underlying mental models. We hope to have demonstrated that the resolution of the instabilities of the financial system and the greening of the economy are intimately coupled.

Investments in renewable technologies are, of course, not the only tools available to stabilize the financial system. However, Keynesian-type counter-cyclical investments promoted by governments will always represent an important component. Investments in renewable energy technologies provide an ideal opportunity for maintaing a stable economic development path while achieving also the desired transformation to a decarbonized global system.

The important next step is to test the simulation models against appropriate data. We have calibrated the models, where available, with so-called "sytylized facts", Maddison (1982, 1995), but have otherwise simply introduced plausible interaction parameters. These need, of course, to be critically examined and further discussed.

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Ben Santer and Gabi Hegerl provided valuable inputs on recent developments in the field of detection and attribution. Dmitry Kovalevsky collaborated in the development of earlier versions of the MADIAMS model hierarchy. Support from the Max Planck Institute for Meteorology, the Global Climate Forum and the EU projects GSDP and EURUCAS is gratefully acknowledged.

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