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Complex Coupled System Dynamics and the Global Warming Policy Problem

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A *Public Domain*, once a velvet carpet of rich buffalo-grass and grama, now an illimitable waste of rattlesnake-bush and tumbleweed, too impoverished to be accepted as a gift by the states within which it lies. Why? Because the ecology of this Southwest happened to be set on a hair trigger.—Aldo Leopold. 1933. The Conservation Ethic. *Journal of Forestry* 33: 636–637.

INTRODUCTION

Most discussion of global environmental problems, such as global warming, have presumed a certain degree of simplicity of dynamical relationships that implies the existence of unique steady-state equilibria for given parameter values, with continuous variation of such equilibria as functions of the relevant parameter values. This has implied a degree of simplicity of analysis of the possible set of policy solutions, even as the difficulty of implementing any of these possible solutions remains very great in the real world of nation states with conflicting interests with regard to such possible policies, as the inability of the world to fully implement even the relatively modest Kyoto Protocol on global warming demonstrates. Thus, the possibility that these dynamical relationships may exhibit various forms of complexity of a nonlinear sort presents a serious additional challenge to global policymakers who already face serious difficulties.

These nonlinearities can present themselves at multiple levels and in multiple ways. Thus, the full global system represents an interaction between ecological and economic components. However, each of these in isolation almost certainly contains crucial dynamic nonlinearities. The combination of these in the larger globally integrated system suggests yet more difficult problems of nonlinear dynamic complexity with the associated conundra facing policymakers.

Although the initial impression may be that the existence of possible nonlinearities in subsystems merely serves to complicate policymaking in a complex world, in some cases we shall see that it may offer possible solutions that might not initially seem to be available. However, in other cases the complications are such as to call for greater precautions than would be the case otherwise in a simpler linear world. In particular, it is the case that chaotic systems tend to remain bounded and thus may represent sustainable solutions despite that apparently erratic nature of the dynamics associated with them. On the other hand, systems in which catastrophic discontinuities can arise present especial dangers and call for greater precautions and investigation to determine the critical boundaries within which the system must be kept in order to maintain sustainability. In effect, we see a conflict between chaos and catastrophe in which the former represents possible sustainability whereas the latter represents the threat of its loss. This conflict rather resembles the conflict between stability and resilience posed by Holling (1973).

Furthermore, even though chaotic systems in isolation may reflect reasonably viable outcomes, when chaotic systems are coupled as may be the case in the globally integrated ecological–economic system, special dynamic outcomes can arise that exhibit substantially greater amplitude of fluctuation as well as catastrophic shifts to drastically different zones of behavior. This presents a serious challenge indeed to analysis and policy.

In this paper we shall broadly consider the system of global climate, especially global warming. Broadly, of course, global warming reflects an input from the global economic system. Chen (1997) argues that the combined interaction of the global climate and economic systems may be a chaotically dynamic system. Although we shall not focus on climate modeling *per se*, it has long been argued that the global climate is chaotic on its own, with Lorenz (1963) having initially identified the phenomenon

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of chaotic sensitive dependence on initial conditions for a climatic model, with this fundamental reality underlying the difficulty of long-term weather forecasting. However, we shall consider the possible complications arising from the coupling of chaotic systems and the emergence of higher-order structures of system dynamics.

This paper will not suggest any specific new policy alternatives. However, it will review the broad approaches to policies for global warming within the context of globally complex dynamics. Within such broadly accepted approaches as the Kyoto Protocol on global warming, certain policies will be emphasized, especially those that provide protection against catastrophic collapse in line with the precautionary principle.

GLOBAL COUPLING, AN INITIAL CONSIDERATION

Before looking more closely at what happens when subsystems behave chaotically or in other complex nonlinear patterns, we shall initially review the model of Chen (1997) in which he shows the possibility of chaotic dynamics for a globally combined climatic–economic system in which none of the subsystems behave chaotically on their own. The model is relatively simple and stylized but demonstrates nevertheless that policy-makers cannot view economic activity as merely exogenous to the broader global system.

The climate model follows Henderson-Sellers and McGuffie (1987) and assumes that there is a global average temperature that is a linear function of the level of global manufacturing output, given by

$$T_{t+1} = (1 - c)(T_t - T_{\mathrm{n}}) + T_{\mathrm{n}} + gX_{\mathrm{m}t}, \quad (1)$$

where $c \in (0, 1)$, T_{n} is normal global average temperature with the t and $t + 1$ subscripts indicating time periods, $g > 0$, and $X_{\mathrm{m}t}$ is global manufacturing output in time t. The economic model has two sectors, agricultural, a, and manufacturing, m, and assumes optimization and equilibrium with a CES utility function of the levels of consumption of agriculture and manufacturing,

$$U(C_{\mathrm{a}t}, C_{\mathrm{m}t}) = (C_{\mathrm{a}t}^{\rho} + C_{\mathrm{m}t}^{\rho})^{1/\rho}, \quad (2)$$

with $C_{\mathrm{i}t} = X_{\mathrm{i}t}$ and the elasticity of substitution $\sigma = 1/(1 - \rho) < 1$. Outputs are linear in sectoral labor, l_{it}, with total labor supply normalized to sum to unity. Agricultural output is also a quadratic function of global temperature. Thus

$$X_{\mathrm{a}t} = (-\alpha T_t^2 + \beta T_t + 1)l_{\mathrm{a}t} \quad (3)$$

$$X_{\mathrm{m}t} = bl_{\mathrm{m}t}, \quad (4)$$

with the market clearing price, p, given by

$$p_t = (-\alpha T_t^2 + \beta T_t + 1)/b. \quad (5)$$

The above gives the equilibrium law of motion of global temperature as

$$T_{t+1} = (1 - c)T_t + g[(bp_t^{1-\sigma})/(1 + p_t^{1-\sigma}). \quad (6)$$

Chen simulates this model for parameter values of $\sigma = 0.5$, $\alpha = 8$, $\beta = 7$, $b = 1$, and $g = 0.6$. The crucial control parameter is c, the adjustment factor for global temperature. For $c \in (0.233, 1)$, the system converges to a steady state. However, as c is lowered below the critical bifurcation value of 0.233, the system undergoes period-doubling bifurcations, converging successively on two-period cycles, four-period cycles, and so forth. The value of $c = 0.209$ is the critical bifurcation point below which the system exhibits aperiodic chaotic dynamics, with sensitive dependence on initial conditions, the so-called "butterfly effect".‡

A sign of this sensitive dependence is given for the case of $c = 0.209$. Chen compares two simulations with initial starting values for T of 0.750 and 0.751, respectively. These imply an initial ratio of agricultural output for the two cases of 1.002. However, at period 36 this ratio has grown to 36.194, a fairly spectacular divergence. On the other hand it must be noted that one of the characteristics of truly chaotic dynamics is that eventually such divergent paths will become arbitrarily close to each other again, reflecting the fundamental boundedness of chaotic dynamics.

Matsumoto and Inaba (2000) extend the Chen model by introducing a varying world population that responds to economic conditions, in turn already responding to climate. They show the possibility of long wave chaotic fluctuations with the possibility of population crashes after century long intervals.

It might be argued that a reasonable approach to this problem might be to control the chaotic fluctuations. A local method was proposed by Ott *et al.* (1990) and a global method is due to Shinbrot *et al.* (1990). In economics, the local method was first applied by Holyst *et al.* (1996) and the global method by Kopel (1997), with Kaas (1998) suggesting the use of both in succession for full and exact macroeconomic stabilization. A variation on the global method due to Pan and Yin (1997) involves merely reducing the bounds of the chaotic dynamics without eliminating chaos as such, an approach that might be tempting to Chen whose model suggests extreme fluctuations of agricultural output on alternative paths.¶

‡Lorenz (1993) describes presenting this colorful term initially in a lecture to meteorologists in 1972 and how it came to be popularly used by many observers. He proposed that a butterfly flapping its wings in Brazil could trigger a hurricane in Texas.

¶It is also possible to induce chaos where none exists when this might be desirable (Schwarz and Triandof, 1996). Allen *et al.* (1993) provide an example in ecology where chaotic population dynamics may reduce the threat of extinction sometimes. Matsumoto (1999) shows that chaotic disequilibrium dynamics may lead to outcomes Pareto superior to market equilibria.

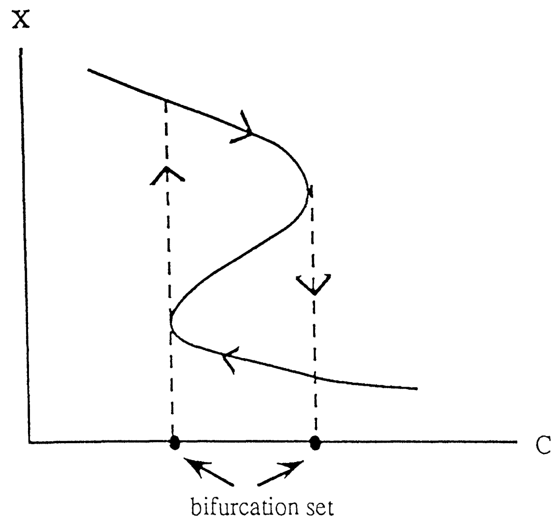

FIGURE 1 Fold catastrophe.

However, all of these techniques involve a far greater knowledge of both the data and the underlying dynamical systems than we realistically possess in either ecological or economic systems in general.

CATASTROPHIC DISCONTINUITIES AND MEAN-FIELD DYNAMICS

Larger scale discontinuities can arise in the sorts of nonlinear dynamical systems that underlie real ecological–economic systems. Even in a simple non-chaotic situation, as demand shifts outwards due to rising income, population, or increasing focus on the health advantages of eating fish, a discontinuity in the equilibria can arise in which the system suddenly jumps from a low price-high fish stock situation to a high price-low fish stock one. The most developed mathematical approach to modeling such dynamic discontinuities has been catastrophe theory, developed by Thom (1975) and Zeeman (1977). This theory arises from studying the structural stability of singularities of certain kinds of nonlinear dynamical systems, especially those with gradient dynamics. It has been applied in many contexts, including some for which the proper mathematical conditions do not hold.[§] Figure 1 shows the equilibrium manifold for the simplest of all catastrophe models, the fold catastrophe, which could arise from the system shown in Fig. 1 if demand were to increase and decrease in succession. Such a situation is relevant to many contexts involving multiple equilibria with hysteresis, even when the precise mathematical conditions required for the application of catastrophe theory do not hold. A variety of such situations have been observed in ecology, including the hysteretic cycle of spruce-budworm outbreaks (May, 1977) and the eutrophication and recovery of freshwater lakes (Carpenter *et al.*, 1998).

Now a problem with both chaos and catastrophe models is their essentially aggregated nature. There is no modeling of emergent dynamics or structure arising from lower level phenomena in them. Everything is on the surface at the same level. However, an alternative approach to modeling discontinuous dynamics that has attracted attention from complexity modelers that offers a partial response to this problem has been that of mean-field dynamics drawn from the study of phase transitions in interacting particle systems of statistical mechanics (Kac, 1968; Spitzer, 1971). Originally applied in economics by Föllmer (1974), this approach has received further development by Brock (1993) and Brock and Durlauf (2001) with numerous applications following in economics (Arthur *et al.*, 1997). It appears to offer real possibilities for modeling ecologic–economic systems.

A simple case considered by Brock and Durlauf involves a set of n agents who might be humans but might also be individuals of other species who face two alternative choices $(-1, 1)$, usually interpreted as being pessimistic and optimistic, with m representing the average of their choices, the mean field. The agents interact with each other with the strength of that interaction being given by J and they also possess an "intensity of choice", equal to β, interpreted in the original statistical mechanics literature as being temperature. The gain from switching choices equals h, which shows the general stochastic state of the system, along with an exogenous stochastic process. Optimal behavior is given by

$$m = \tanh(\beta J + \beta h) \quad (7)$$

with tanh being the hypertangent function. Brock and Durlauf (2001) show that a critical value for this system occurs at $\beta J = 1$. The case for which $h = 0$ is depicted in Fig. 2 which is from Rosser (1999, p. 179), and which shows a bifurcation with two stable but distinct equilibria for cases where either the strength of interaction or the intensity of choice are sufficiently high. Such outcomes can be manifested by agents clustering to act together in some coherent manner, a case of emergent structure. In the original statistical mechanics literature such bifurcations were seen as indicators of phase transitions between states of matter such as the boiling or freezing of water.[||] Some have suggested that for various reasons the global climatic system may be subject to large changes within relatively short times (Bryson and Murray, 1977).

[§]For reviews of applications in economics and related disciplines see Guastello (1995), Puu (2000) and Rosser (2000b). For a more complete discussion of underlying mathematical issues see Arnol'd (1992).

[||]This example was a favorite for dialectical theorists when contemplating the nature of qualitative change arising from quantitative change. Rosser (2000c) discusses this in the context of nonlinear dynamics, and Georgescu-Roegen (1971) has applied the dialectical approach to ecological economics.

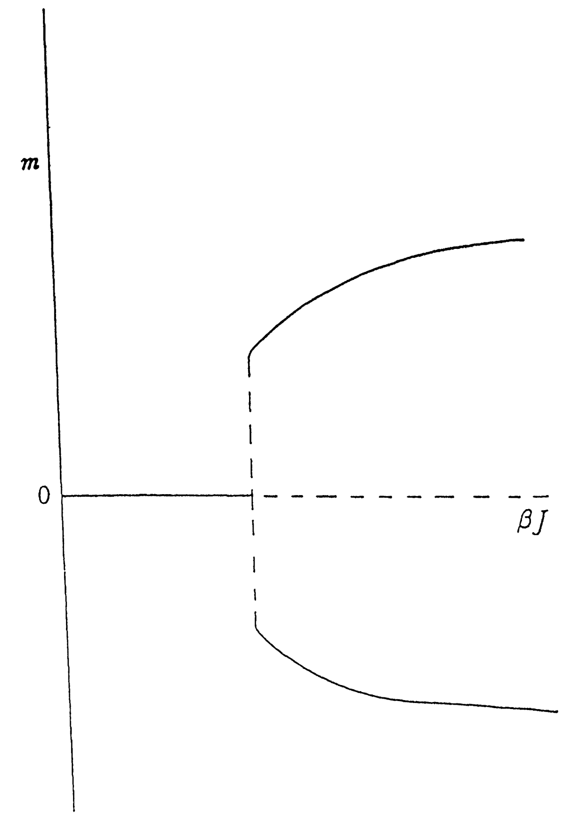

FIGURE 2 Bifurcation of mean-field equilibria.

THE HIERARCHY COMPLICATION

The above discussion leads us to a more difficult source of complexity, the problem of levels of hierarchy interacting with each other. Global climate may negatively impact a fishery, as in the case of the collapse of the Peruvian anchoveta fishery in 1972, attributed by some to global climatic changes (Johnston and Suitenen, 1996). But it is highly doubtful that a fishery can in turn negatively impact global climate. Nevertheless it appears that there are cases where events at a lower level of hierarchy can impact those at a higher level.

The question of how to model hierarchical systems has been a matter of greater attention in ecology than in economics, with Simon (1962) providing an initial framework used by many in different fields. Among those developing approaches in ecology are Allen and Starr (1982), O'Neill *et al.* (1986) and Holling (1992). Efforts to model dynamics within hierarchical systems have used a variety of approaches including the synergetics model of Haken (1983)[#] and associated models of entrainment at different levels of hierarchy (Nicolis, 1986; Rosser *et al.*, 1994). Rosser *et al.* in particular model the possible emergence of new levels of hierarchy, the *anagenetic moment.*

Aoki (1996) provides an intriguing approach that draws on the synergetics-derived master equation model of Weidlich and Braun (1992). This approach allows for the introduction of mean-field dynamics as described in the previous section. In his work the mean field effects are seen as due to externalities that bring about higher level coherences and emergent structures. Sudden structural changes in dynamical hierarchical systems are associated with fixed points in the coarse graining or aggregation of microunits (Dyson, 1969). A sequence of phase transitions can arise as a sequence of clusters of equilibria (Rose *et al.*, 1990).

In many of these models of hierarchy it is assumed that higher levels constrain lower level dynamics, or "slave" them to use the terminology of synergetics. However, the possibility arises again in association with the existence of certain critical points of a "revolt of the slaved variables" (Diener and Poston, 1984) in which a change in lower level variables can destabilize the higher levels and bring about changes at those levels. Holling (1986) characterizes such cases as ones of "local surprise and global change". It can be argued that in such cases there may exist *critical levels* whose stability must be ensured in order to maintain the stability of the larger hierarchical system at both higher and lower levels. Such a level may operate much like a "keystone species" within more general ecosystems (Vandermeer and Maruca, 1998).

The problem of appropriate levels is a crucial one for policy. This problem is closely linked with the issue of assigning property rights, or to be more precise, rights to control access to biotic resources. Rosser (1995, 2000a) emphasizes particularly that such rights must correspond to the appropriate level of the relevant combined ecologic–economic system. This is more widely known as the *Scale-Matching Principle*, the idea that policy should be appropriate to the scale of the ecosystem (Wilson *et al.*, 1999).

GLOBALLY COUPLED DYNAMICS RECONSIDERED

We are now in a position to reconsider the possible nature of the dynamics of the globally coupled ecologic–economic system as initially presented above in the Chen (1997) model. However, we now wish to contemplate a more general set of relationships in order to bring out certain potentially emergent phenomena and associated threats to the global noöspheric system.[**] Whereas in the Chen model relatively simple climatic and economic subsystems combined to generate a chaotic total system, now we wish to consider the dynamics of a case where the subsystems which are globally coupled are themselves already chaotic.

[#]For general applications of synergetics to economics, see Zhang (1991).

[**]Vernadsky (1945) introduced the concept of the noösphere to describe the interaction between human consciousness and the biosphere at the global level. Rosser (1992) discusses the evolutionary interaction between human and non-human parts of the global system.

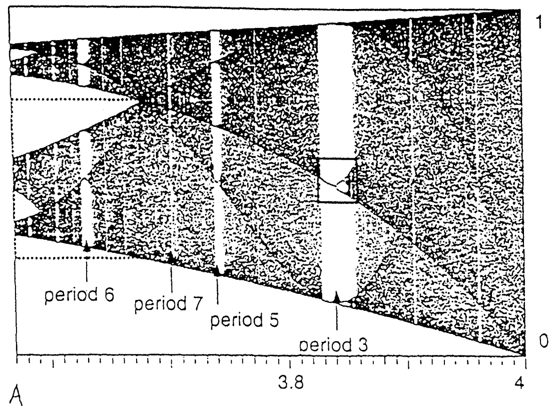

FIGURE 3 Periodic windows of logistic map.

We have already noted that Lorenz (1963, 1993) has argued that the climatic system is fundamentally chaotic, a widely held view. Various authors have argued for the actual existence of chaotic dynamics in various agricultural markets, especially those marked by cyclical cobweb dynamics (Chavas and Holt, 1991, 1993; Finkenstädt and Kuhbier, 1992). Certainly there is a link from climate to agriculture, and there is probably a link back from agriculture to climate, both through agricultural technology and the alteration of local climates as well as through the impact of agriculture on industry.

Thus, we shall consider the dynamics presented by Shibata and Kaneko (1998a) in a model of globally coupled logistic maps with the individual subsystems exhibiting chaotic dynamics and the overall system characterized by a mean-field dynamic element. As shown by Kaneko (1990) such a system can subsume certain problems of hierarchy as well. Shibata and Kaneko pose the system of globally coupled maps of N elements by

$$X_{t+1}(i) = (1-\varepsilon)[1 - aX_t^2(i)] + (\varepsilon/N)\sum_{j=1}^{N}[1 - aX_t^2(j)], \tag{8}$$

with the second term representing the mean field effect, h, multiplied by the coupling strength, ε. The control parameters in this multidimensional system are composed from the coupling strength, ε, the nonlinearity parameter, a, and the number of elements, N.

Shibata and Kaneko examine the bifurcation structure of this system as the parameters vary and discover the emergence of collective behavior.[††] This collective behavior takes the form of non-chaotic oscillations of substantially greater amplitude than in the desynchronized chaotic state. Also, hysteresis and multiple coexisting attractors can arise along with these collective dynamics. Such larger amplitudes of oscillation suggest a much greater threat than arises in the essentially simpler models of merely chaotic global dynamics.

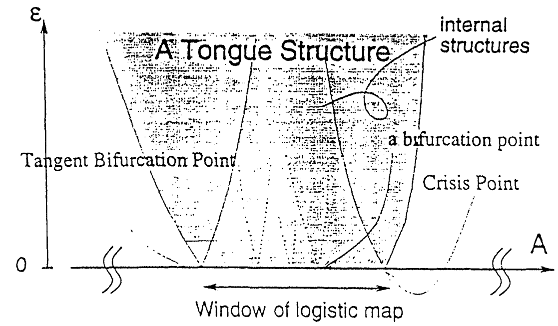

FIGURE 4 Shibata-Kaneko coupled logistic tongue structure.

More particularly the collective dynamics emerge in tongue-like structures that appear in the periodic windows of the chaotic zone of the bifurcation diagram of the single logistic map. Such a pattern of periodic windows is shown in Fig. 3 (from Peitgen *et al.*, 1992, p. 682).

Within a given periodic window of the single logistic map bifurcation diagram, a particular tongue-like structure within which large-amplitude collective behavior may occur will increase in size with both the degree of coupling strength, ε, and also that variable times amplitude of the mean-field variation, with the width of the tongue increasing with ε^2. There will be bifurcations associated with mean-field dynamic oscillations within a given tongue-like structure, even when the coupling strength and nonlinearity control parameters remain constant. The pattern of such a tongue-like structure is shown in Fig. 4 from Shibata and Kaneko (1998a, p. 198). The horizontal axis in Fig. 4 is given by

$$A = (1-\varepsilon)[1 - \varepsilon + \varepsilon(h)a]. \tag{15}$$

GLOBAL WARMING POLICY IN THE FACE OF ECOLOGIC–ECONOMIC COMPLEXITY

There is little doubt that the possible existence of such nonlinear complexities in the global ecologic–economic system of climate interacting with economy severely complicates the difficulties facing policymakers. The obvious issue that must be dealt with is a greater focus on determining critical boundaries and threshold levels for systems that must be kept within in order to avoid catastrophic collapses. This is easier said than done, needless to say, but the effort to do this is generally known as the *Precautionary Principle*. Beyond this a number of points can be made with respect to the complicated and controversial problem of global warming.

The effort made at Kyoto would seem to be a minimum that should be implemented. But, we know that there is resistance on the part of some nations which suggests that maximum flexibility should be adopted in order to achieve the agreed-upon goals, including market mechanisms and other innovations as urged by Sonneborn (1999) and Zhang (1999a,b). This is especially appropriate given that

[††]Shibata and Kaneko (1998b) present algorithms for estimating emergently collective chaos.

the expected costs and benefits associated with the policies are very unevenly distributed about the globe.

Indeed, great controversy surrounds this issue at several levels. One involves the very science underpinning the climatic forecasts, with those forecasts having been successively adjusted several times. Skeptics, such as Michaels and Balling (2000) charge that mitigating factors such as possible increased uptake of carbon dioxide by the oceans has not been fully included in the models and note the discrepancies between ground and atmospheric temperature measurements.

On the other hand, it is unclear that there has been a sufficient incorporation of likely destabilizing positive feedback effects in the models, with the impact of *albedo*, that is surface reflectivity, being a widely noted factor. The historical record suggests that the transition in and out of ice ages occurred quite quickly which may reflect such albedo phenomena, as increasing ice cover can sharply lower the temperature due to greater reflectivity (Bryson and Murray, 1977), and the opposite happening as ice cover contracts, the more relevant example for the current situation. This latter suggests the possibility of much greater increases in global temperature than have been forecast as ice cover is reduced below certain critical levels. Such possibilities would also seem to be the implication of the kinds of models discussed in the immediately preceding section of this paper in which globally coupled systems may exhibit large-scale collective oscillations of high amplitude. Increasingly some insurance companies have begun to worry about how to deal with such possibilities of major global warming (Tucker, 1997).

Furthermore, there are widespread debates and controversies about the economic impacts of any global warming. Nordhaus (1993) presents optimal global carbon taxes based on mid-range estimates of damages. By projecting lower economic growth, Jorgenson and Wilcoxen (1991) project lower economic losses, while Cline (1992) projects higher economic losses due to assuming a lower discount rate. Mendelsohn *et al.* (1994) project lower agricultural losses using a "Ricardian" approach that allows for substituting crops in impacted regions, estimates that have been challenged by Kauffman (1998). Complicating these estimates as well as the policy response is the fact that some areas can experience extremely adverse impacts, such as nations that might disappear completely if ocean levels rise, whereas others might actually be better off, such as very cold ones that might experience increased agricultural output and lower heating costs. Shogren (1999) suggests that the Kyoto Protocol will only yield a clear net benefit if catastrophe is highly likely, with most of the benefits going to less developed countries in the future. Again, these kinds of variations suggest the importance of implementing policies that are sufficiently flexible at national levels and allow for trading between nations of the costs of adjustment.

We note that the old problem of the appropriate discount rate is running through all these questions. We see from the comparing the Cline and Nordhaus estimates that a lower discount rate raises the estimated costs of global warming in terms of present value. This is not a new issue for environmental or ecological economics. At this point we shall simply note the recent discussions involving efforts to balance off the present and the future through such ideas as the *green golden rule* (Chichilnisky *et al.*, 1995) which seem to lead to ideas of using higher discount rates in the near term but lower ones for evaluating outcomes farther in the future. We note that the formal models of this rule involve imposing constraints on future outcomes that suggest again the need for being concerned with critical boundaries and thresholds that the global system must be kept within.

Finally we must deal with the crucial and unresolved institutional issue. In contrast to world trade and world peace, there is no accepted global entity designated to deal with environmental issues in general. What we have are a series of *ad hoc* treaties, accords, protocols, and partial arrangements that deal with a variety of issues separately. The Kyoto Protocol on global warming is an example of one of these, but it exists outside of any broader institutional or enforcement framework, and indeed remains unratified by the most important party to it, the United States.

Nevertheless, it must be recognized that the existence of such a global institution or body is no guarantee that treaties or accords or protocols or agreements will be obeyed or followed. The existence of the World Trade Organization has not ended disagreements and conflicts over trade, including violations of existing agreements by individual countries. Likewise, the existence of the United Nations most certainly has not guaranteed the existence of world peace. Many of the global environmental agreements that have been reached have worked well and been widely accepted. Others have not. The ultimate dependence for agreements to work upon their genuine acceptance by the nations involved remains an argument for seeking out flexible and innovative approaches to these difficult policy issues.

Perhaps the world political economic system will evolve to a point where a genuine global environmental agency will emerge. But until that time, and even perhaps after such a time, we must work to convince nations and groups within nations that it is in their own ultimate best interest to accept and obey the agreements that have been reached for dealing with global environmental problems.

CONCLUSIONS

In an integrated global ecologic–economic system a variety of complex nonlinear dynamics are possible that complicate global policymaking efforts. Chaotic dynamics and catastrophic discontinuities can arise. These can be exacerbated in globally coupled systems with evolving mean-field dynamics in which higher-order oscillations of much greater magnitude may emerge. These difficulties present a great challenge for policymaking in connection with global warming.

Such difficulties tend to emphasize the need to put in place safeguards about remaining within critical boundaries or thresholds, in short a serious application of the Precautionary Principle. They also emphasize the need to clearly identify relevant scale levels in hierarchical systems at which policies and access controls should be implemented, in short the Scale-Matching Principle. Flexibility of policies in an adaptive framework would seem to be appropriate as well. But these efforts are all contingent on the emergence of appropriate global institutions and arrangements for dealing with these policy problems. This is an evolutionary process that has yet to achieve a critical anagenetic moment.

Let us conclude by contrasting again chaotic and catastrophic dynamics in these models. Contrary to many expectations, chaotic dynamics may actually be a desirable outcome for sustainability of systems, as long as the bounds of those dynamics remain within sustainable levels. Agents may even be able to learn to believe and follow such dynamics through simple boundedly rational rules of thumb (Rosser, 2000a). The greater threat comes from catastrophic discontinuities associated with crossing critical threshold levels or from non-chaotic oscillations of much greater amplitude that can emerge in coupled systems out of chaotic underlying subsystems. Thus, it is catastrophe rather than chaos that appears to be the greater threat to the globally integrated noösphere.‡‡

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‡‡For a discussion of when chaos and catastrophe are "good" and "bad," see Rosser (1991, Chap. 17).

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