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Dynamics of climate and ecosystem coupling: abrupt changes and multiple equilibria

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Interactions between subunits of the global climate–biosphere system (e.g. atmosphere, ocean, biosphere and cryosphere) often lead to behaviour that is not evident when each subunit is viewed in isolation. This newly evident behaviour is an emergent property of the coupled subsystems. Interactions between thermohaline circulation and climate illustrate one emergent property of coupling ocean and atmospheric circulation. The multiple thermohaline circulation equilibria that result caused abrupt climate changes in the past and may cause abrupt climate changes in the future. Similarly, coupling between the climate system and ecosystem structure and function produces complex behaviour in certain regions. For example, atmosphere–biosphere interactions in the Sahel region of West Africa lead to multiple stable equilibria. Either wet or dry climate equilibria can occur under otherwise identical forcing conditions. The equilibrium reached is dependent on past history (i.e. initial conditions), and relatively small perturbations to either climate or vegetation can cause switching between the two equilibria. Both thermohaline circulation and the climate–vegetation system in the Sahel are prone to abrupt changes that may be irreversible. This complicates the relatively linear view of global changes held in many scientific and policy communities. Emergent properties of coupled socio-natural systems add yet another layer of complexity to the policy debate. As a result, the social and economic consequences of possible global changes are likely to be underestimated in most conventional analyses because these nonlinear, abrupt and irreversible responses are insufficiently considered.

Keywords: hysteresis; thermohaline circulation collapse; atmosphere–biosphere interactions; multiple equilibria; emergent properties; abrupt nonlinear climate system behaviour

1. INTRODUCTION

Most global systems are inherently complex, consisting of multiple interacting subunits. Scientists frequently attempt to model these complex systems in isolation (often along distinct disciplinary lines), producing internally stable and predictable behaviour. However, real-world coupling between subsystems often causes the set of interacting systems to exhibit new collective behaviours—often called 'emergent properties'—not demonstrable by models that do not also include such coupling.

Furthermore, responses of the coupled systems to external forcing can become quite complicated. For example, one emergent property, increasingly evident in climate and biological systems, is that of irreversibility or hysteresis—changes persist in the new post-disturbance state even when the original forcing is restored. This irreversibility can be a consequence of multiple stable equilibria in the coupled system—that is, the same forcing might produce different responses depending on the pathway followed by the system. Therefore, anomalies can push the coupled system from one equilibrium to another, each of which has very different sensitivity to disturbances (i.e. each equilibrium may be self-sustaining).

Exponential increases in computational power have encouraged scientists to turn their attention to broadly focused projects that couple multiple disciplinary models. GCMs of the atmosphere and oceans, for example, now allow exploration of emergent properties in the climate system resulting from interactions between the atmospheric, oceanic, biospheric and cryogenic components.

We outline several examples of processes that exhibit complex behaviour due to interactions between subsystems of the climate system including, in one example, the socio-economic system. These include multiple stable equilibrium states of the THC in the North Atlantic and of the atmosphere–biosphere interactions in western Africa.

A common view of the climate system and ecosystem structure and function is that of path independence or ergodicity. However, the multiple stable equilibria for both THC and for atmosphere–biosphere interactions in West Africa suggest a more complex reality. In such systems the equilibrium state reached is dependent on the initial conditions of the system. Crossing thresholds can lead to unpredictable or irreversible changes. Furthermore, such complex processes have an implication for effective policymaking. Incorporating possibly damaging effects of changes in THC into modelling of climate change policy can significantly alter policy recommendations and lead to the discovery of emergent properties of the coupled social–natural system.

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2. THERMOHALINE CIRCULATION

THC in the Atlantic brings warm tropical water northward, raising SST *ca.* 4 °C relative to SST at comparable latitudes in the Pacific (Levitus 1982). The warm SST in the North Atlantic provides heat and moisture to the atmosphere, thereby warming Greenland and western Europe by roughly 5–8 °C and increasing precipitation throughout the region (Broecker 1997; Stocker & Marchal 2000).

Temperature and salinity patterns in the Atlantic create the density differences that drive THC. As the warm surface waters move to higher northern latitudes, heat exchange with the atmosphere causes the water to cool and sink at two locations: one south of the GIS ridge in the Labrador Sea and the other north of the GIS ridge in the Greenland and Norwegian Seas (Killworth 1983; Rahmstorf 1999). Water sinking at the two sites combines to form NADW, which then flows to the southern hemisphere via the deep WBC. From there NADW mixes with the circumpolar Antarctic current and is distributed to the Pacific and Indian Oceans where it upwells, warms and returns to the South Atlantic. As a result, there is a net northward flow of warm, salty water at the surface in the North Atlantic.

Palaeoclimate reconstruction and model simulations suggest there are multiple equilibria for THC in the North Atlantic, including complete collapse of circulation. These multiple equilibria constitute an emergent property of the coupled ocean–atmosphere system. Switching between the equilibria can occur as a result of temperature or freshwater forcing. Thus, the pattern of THC that exists today could be modified by an infusion of fresh water at higher latitudes or through high-latitude warming and the concomitant reduction in the Equator–pole temperature gradient. These changes may occur if climate change increases precipitation, causes glaciers to melt, or warms high latitudes more than low latitudes, as is often projected (IPCC 1996).

Further research has incorporated this behaviour into coupled climate–economic modelling, characterizing additional emergent properties of the coupled climate–economic system (Mastrandrea & Schneider 2001). Again, this coupled multisystem behaviour is not revealed by single-discipline submodels alone; e.g. choices of model parameter values such as the discount rate determine whether emissions mitigation decisions made in the near term will prevent a future THC collapse or not—clearly a property not obtainable by an economic model *per se*.

Rahmstorf (1996) presents a schematic stability diagram of THC, based on his modification of the conceptual model of salinity feedback developed by Henry Stommel. Figure 1 demonstrates three possible classes of THC equilibrium states under different levels of freshwater forcing, and the theoretical mechanisms for switching between them. These include two classes of deep water formation, one with sinking in the Labrador sea and north of the GIS ridge and one with sinking north of the GIS ridge alone, and one class of complete overturning shutdown. This formulation indicates that switching between stable equilibria can occur very rapidly under certain conditions. The palaeoclimatic record supports this, suggesting rapid and repeated switching between equilibria, in the order of years to decades (Alley *et al.* 1993; Bond *et al.* 1997). Evidence indicates that during glacial periods, partial collapse of the continental ice sheets into the North Atlantic freed large amounts of fresh water through extensive iceberg releases (Seidov & Maslin 1999).

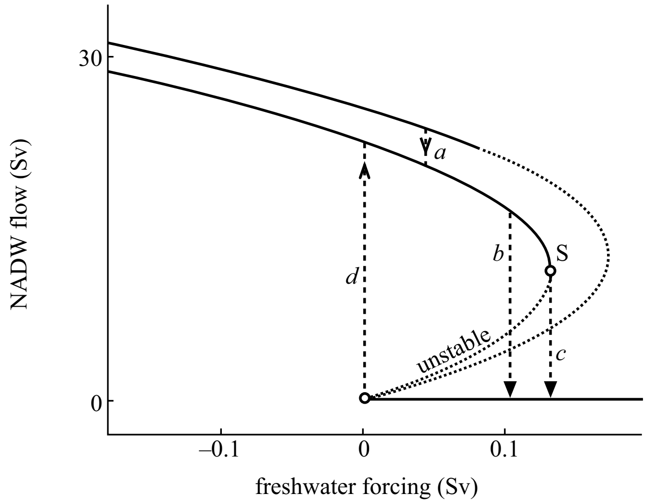

Figure 1. Schematic bifurcation diagram for NADW flow, as derived from GCM results and theoretical models. Solid lines show stable equilibrium states; dotted lines show unstable states. The upper two solid lines correspond to equilibria with different NADW formation sites, the bottom solid line corresponds to an equilibrium without NADW formation ('NADW off'). The uppermost stable branch is not drawn out to its saddle-node bifurcation, indicating that it becomes convectively unstable before reaching such a point. Examples of the four basic transition mechanisms are shown by dashed lines: (*a*) local convective instability, a rapid shutdown or start-up of a convection site; (*b*) polar halocline catastrophe, a total rapid shutdown of North Atlantic convection; (*c*) advective spin-down, a slow spin-down process triggered when the large-scale freshwater forcing exceeds the critical value at Stommel's saddle-node bifurcation S while convection initially continues; (*d*) start-up of convection in the North Atlantic from a 'NADW off' state. The convective transitions *a*, *b*, *d* can be triggered either when a gradual forcing change pushes the system to the end of a stable branch or by a brief but sufficiently strong anomaly in the forcing. From Rahmstorf (1999).

Complex GCMs suggest that future climate change could cause a similar slowdown or even collapse in THC overturning (Manabe & Stouffer 1993; Wood *et al.* 1999). The SCD developed by Schneider & Thompson (2000) incorporates a simple density-driven set of Atlantic Ocean boxes that mimic the results of complex models, but is sufficiently computationally efficient that the SCD facilitates sensitivity analysis of key parameters and generates a domain of scenarios that show abrupt collapse of THC (figure 2). Model results (Schneider & Thompson 2000; Stocker & Marchal 2000) suggest that both the amount of GHGs entering the atmosphere and also the rate of entry will affect the THC overturning.

If warming reduces the ability of surface water to sink in high latitudes, this will interfere with the inflow of warm water from the south. Such a slowdown will cause local cooling—re-energizing the local sinking, serving as a stabilizing negative feedback on the slowdown. However, the

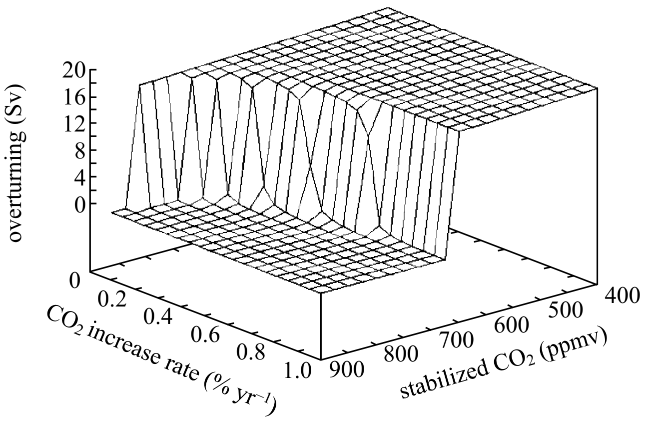

Figure 2. Equilibrium results of the SCD model under different forcing scenarios, from Schneider & Thompson (2000). THC overturning in sverdrups (1 Sv = 10^6 m^3 s^{-1}) is shown on the vertical axis as a function of the rate of CO_2 increase in the atmosphere and the stabilization concentration. Higher stabilization levels and more rapid rates of CO_2 increase make a THC collapse more probable.

initial slowdown of the strength of the Gulf Stream reduces the flow of salty subtropical water to the higher latitudes of the North Atlantic. This would act as a destabilizing positive feedback on the process by further decreasing the salinity of the North Atlantic surface water and reducing its density and thus further inhibiting local sinking. The rate at which the warming force is applied to the coupled system could determine which of these opposing feedbacks dominates, and subsequently whether a THC collapse occurs.

Recent research efforts have connected this abrupt nonlinearity to integrated assessment of climate change policy. The DICE model of William Nordhaus (1994) is a simple optimal growth model. Given a set of explicit value judgements and assumptions, the model generates an optimal future forecast for a number of economic and environmental variables. It does this by maximizing discounted utility (satisfaction from consumption) by balancing the costs to the economy of GHG emissions abatement (a loss in a portion of GDP caused by higher carbon energy prices) against the costs of the build-up of atmospheric GHG concentrations. This build-up affects the climate, which in turn causes 'climate damage', a reduction in GDP determined by the rise in globally averaged surface temperature due to GHG emissions. In some sectors and regions such climate damages could be negative—i.e. benefits—but DICE aggregates across all sectors and regions (e.g. the discussions in chapters 1 and 19 of IPCC (2001)) and thus assumes that this aggregate measure of damage is always a positive cost.

Mastrandrea & Schneider (2001) have developed a modified version of Nordhaus's DICE model called E-DICE, containing an enhanced damage function that reflects the higher damages that would probably result when abrupt climate changes occur. If climate changes are smooth and thus relatively predictable, then the foresight afforded increases the capacity of society to adapt; hence damages will be lower than for very rapid or less anticipated changes such as abrupt unanticipated events—'surprises' such as a THC collapse. It is probable that, even in a distant future society, the advent of abrupt climatic changes would reduce adaptability and thus increase damages relative to smoothly varying, more foreseeable changes.

Since the processes that the models ignore by their high degree of aggregation require heroic parametrizations, the quantitative results are only used as a tool for insights into potential qualitative behaviours. The results reveal an emergent property of the coupled climate–economy system that is not shown by separate single models of nature or society alone. Because of the abrupt nonlinear behaviour of the SCD model, the E-DICE model produces a result that is also qualitatively different from DICE with its lack of internal abrupt nonlinear dynamics. A THC collapse is obtained for rapid and large CO_2 increases in the SCD model. An 'optimal' solution of conventional DICE can produce an emissions profile that triggers such a collapse. However, this abrupt nonlinear event can be prevented when the damage function in DICE is modified to account for enhanced damages created by this THC collapse and THC behaviour is incorporated into the coupled climate–economy model.

The coupled system contains feedback mechanisms that allow the profile of carbon taxes to increase sufficiently in response to the enhanced damages in order to lower emissions sufficiently to prevent the THC collapse in an optimization run of E-DICE. The enhanced carbon tax actually 'works' to decrease emissions and thus avoid future damages. Keller *et al.* (2000) support these results, finding that significantly reducing CO_2 emissions to prevent or delay potential damage from an uncertain and irreversible future climate change such as THC collapse may be cost effective. However, the amount of near-term mitigation the DICE model 'recommends' for the reduction of future damage is critically dependent on the discount rate. Thus, for low discount rates (less than 1.8% in one formulation; figure 3) the present value of future damages creates a sufficient carbon tax to keep emissions below the trigger level for the abrupt nonlinear collapse of the THC a century later. However, a higher discount rate sufficiently reduces the present value of even catastrophic long-term damages that abrupt nonlinear THC collapse becomes an emergent property of the coupled socio-natural system—with the discount rate becoming the parameter that most influences the 22nd-century behaviour of the climate model.

Although these highly aggregated models are not intended to provide high-confidence quantitative projections of coupled socio-natural system behaviours, we believe that the bulk of integrated assessment models used to date for climate policy analysis—and which do not include any such abrupt nonlinear processes—will not be able to alert the policymaking community to the importance of abrupt nonlinear behaviours. At the very least, the ranges of estimates of future climate damage should be expanded beyond that suggested in conventional analytical tools to account for such nonlinear behaviours (Moss & Schneider 2000).

3. VEGETATION COVER AND CLIMATE DYNAMICS

The potential for multiple equilibria in the coupled atmosphere–biosphere system has received increasing attention in recent years. Several regions of the world

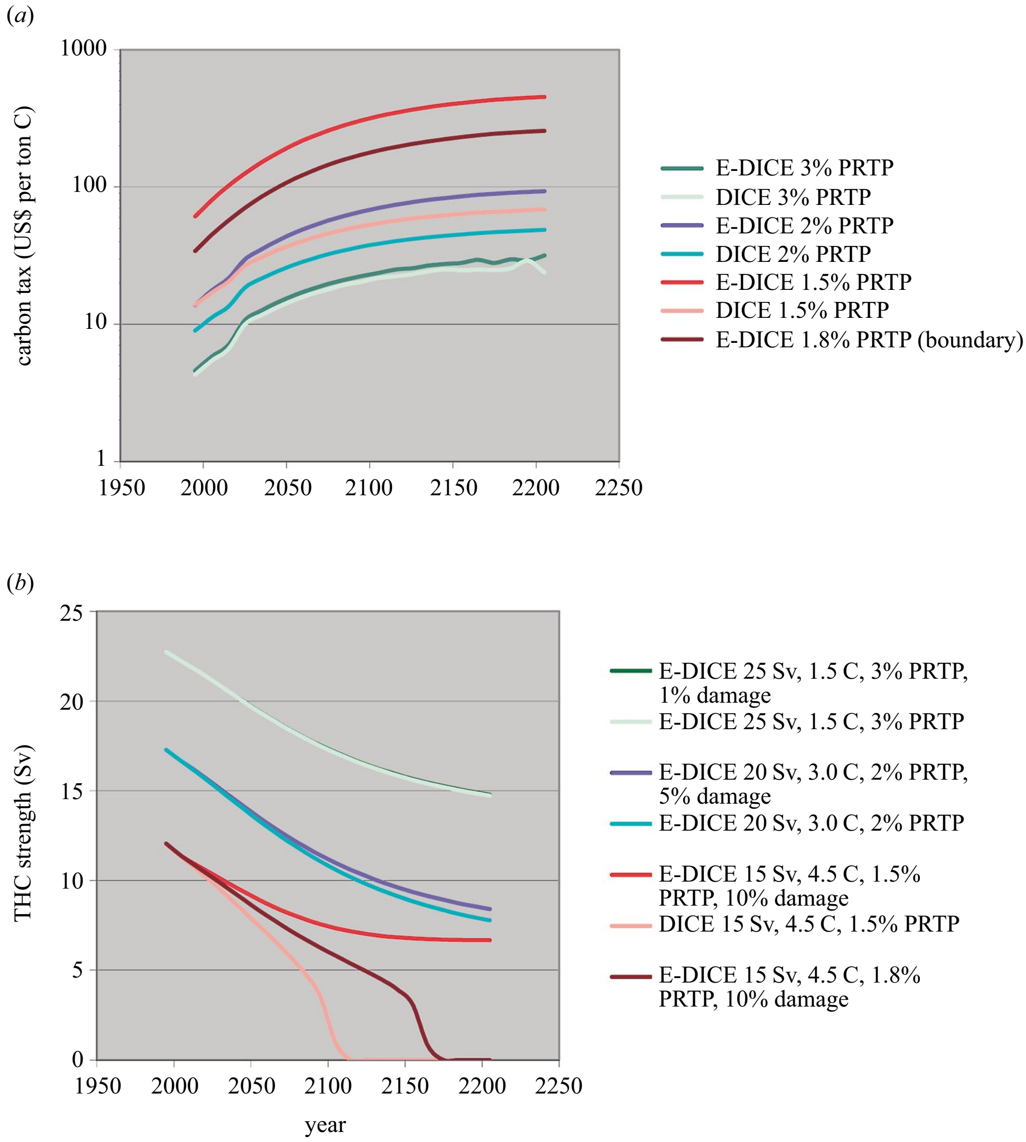

Figure 3. (*a*) Optimal carbon taxes for E-DICE and DICE, and (*b*) the THC overturning profiles associated with those scenarios. The curves delineate a range of solutions, and illustrate the sensitivity of the E-DICE model to the PRTP. As the PRTP decreases, the increase in carbon tax grows when THC enhanced damages are included. The red family of curves illustrate an emergent property of this coupled socio-natural system. Under the optimal DICE run (light red curve), THC collapses abruptly (for the parameters shown in the key). When potential THC damages are incorporated, the increase in optimal carbon tax reduces emissions sufficiently to prevent the collapse (red curve). However, when PRTP is increased from 1.5% to 1.8% or greater, the discounted present value of the enhanced damages is insufficient to lower emissions below the threshold that causes abrupt THC collapse.

appear to exhibit multiple stable equilibria, with the equilibrium realized depending on the initial conditions of the coupled system. Other regions appear to have a single stable equilibrium, at least under current conditions.

Regions with multiple equilibria may be characterized by a greater sensitivity of precipitation to either changes in total net surface radiation or changes in the partitioning of net surface radiation between sensible and latent heat fluxes. Either or both can accompany vegetation change (Eltahir 1996). Such regions include West Africa, where the strength of the tropical monsoon influences the vegetation distribution but also depends upon that vegetation (Eltahir 1996; Zheng & Eltahir, 1997, 1998; Wang & Eltahir 2000*a*,*b*), and possibly the Amazon basin, where the availability of water for precipitation may be dependent on rooting depth and the type of vegetation present (Kleidon & Heimann 1999).

The boreal forest–tundra boundary, which influences albedo, is a third potential region where the atmosphere–biosphere system could have multiple equilibria. Boreal forest decreases albedo relative to tundra (i.e. snow-covered treeless ground reflects much more energy than snow-covered forests), thereby increasing total net surface radiation and temperature. Boreal forest also requires a longer growing season (i.e. higher temperatures) than tundra, suggesting the potential for positive feedbacks between vegetation and climate.

Indeed, simulations suggest that boreal forests raise both winter and summer temperature relative to tundra (Bonan *et al.* 1992). In part, this is due to the direct (local) effect of the albedo decrease over land during the spring and autumn. In part, the increase in summer temperature results from earlier melting of sea ice and the concomitant increase in summertime SSTs (a distant scale feedback). Therefore, shifts in vegetation between forest and tundra constitute a positive feedback to changes in the climate system. Tundra (boreal forest) has a higher (lower) albedo, which decreases (increases) net radiation and temperature, thereby leading to conditions that are more favourable for tundra (boreal forest). If these feedbacks are sufficiently strong, multiple equilibria may be possible given different distributions of forest and tundra. Therefore, the climate–biosphere system could occupy either the colder tundra state or the warmer boreal forest state, depending on the initial distribution of vegetation or other factors such as fire disturbance regimes.

On the basis of the results reviewed below, the forest–tundra boundary appears to be a single stable equilibrium, at least at a scale relevant to the climate system. However, evidence suggests that certain regions in the subtropics indeed have multiple stable equilibria that depend upon initial vegetation distribution.

Several areas where multiple equilibria exist in the coupled atmosphere–biosphere system suggest a linkage between regional aridity and vegetation cover. For example, using a coupled global atmosphere–biome model, Claussen (1998) produces two separate equilibrium solutions for North Africa and Central East Asia when initialized with different land surface conditions.

The first equilibrium, obtained when the model is initialized with bright sand desert on all ice-free land, is drier, with a distribution of subtropical deserts similar to the present day. The other equilibrium, obtained when the model is initialized with forest, grassland or dark desert on all ice-free land, is moister with a concomitant northward shift of vegetation into what are now arid regions. In the rest of the world different initial conditions produce a single equilibrium in the atmosphere–biosphere system as modelled by Claussen (1998).

A similar study compared simulations with vegetation initialized as either forest or desert (Kleidon *et al.* 2000). The comparison between these 'green' and 'desert' worlds again illustrates that some regions are sensitive to the initial vegetation while other regions have only a single equilibrium under current conditions. In particular, regions of Africa, South Asia and Australia produced different stable atmosphere–biosphere equilibria, depending on whether the initialized vegetation was forest or desert. In contrast, such simulations produce a single equilibrium for both the 'green' and 'desert' world in other regions.

The Amazon is another candidate for multiple equilibria in the coupled climate–vegetation system. Kleidon & Heimann (1999) studied the interactions between vegetation type, rooting depth and climate in the Amazon basin. During the dry season, the water transpired by plants contributes substantially to atmospheric moisture, altering the partitioning of net radiation between sensible and latent heat fluxes and increasing relative humidity. In their simulation, vegetation type determines rooting depth, which partly determines the availability of soil moisture for evapotranspiration. Comparison between simulations that differed in rooting depth revealed that the dry season is warmer, and lasts longer, when vegetation with a shallower rooting depth is present than when vegetation with deeper roots is initialized (Kleidon & Heimann 1999).

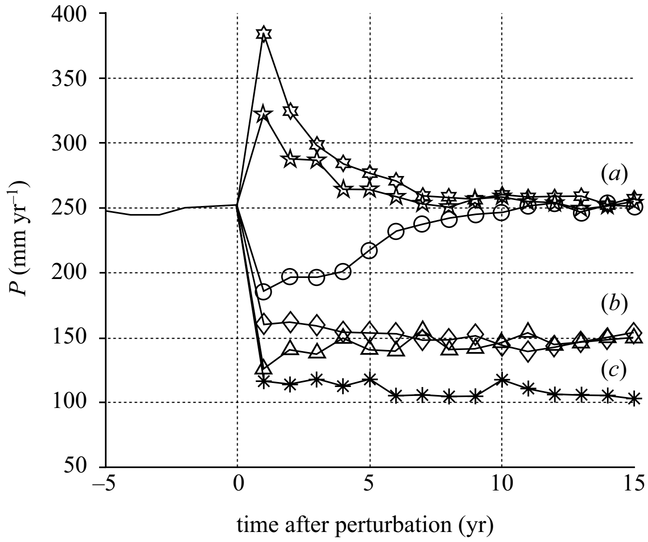

Figure 4. Response of the coupled atmosphere–biosphere system to vegetation perturbations for the Sahel using a synchronously coupled biosphere–atmosphere model (as described by Wang & Eltahir 2000*b*) and starting from a vegetation distribution for West Africa close to the present-day distribution. LAI shows a similar pattern to that shown here for precipitation. Three equilibria are obtained depending on the magnitude of the vegetation perturbation. (*a*) The coupled climate–vegetation system is stable to perturbations in which vegetation is degraded by 50%, or increased by 50 and 100%; thus, vegetation and precipitation recover to pre-disturbance values. (*b*) Perturbations in which 60 and 75% of the vegetation is degraded and results in a second equilibrium in the coupled climate–vegetation system. (*c*) Perturbation in the form of 80% degradation of vegetation results in a third equilibrium. Six-point stars, +100%; five point stars, +50%; circles, −50%; diamonds, −60%; triangles, −75%; asterisks, −80%. From Wang & Eltahir (2000*b*).

Under these conditions, vegetation response to disturbance could potentially cause either positive or negative feedbacks to the climate system. If rooting depth increases (decreases) as a response to increasing dryness (wetness), the feedback would be negative. Deeper (shallower) roots would transpire more (less) causing wetter (drier) conditions. However, the feedback could also be positive if the vegetation response to drier (wetter) climatic conditions results in shallower (deeper) root depth with a concomitant reduction (increase) in transpiration. This positive feedback to atmosphere–biosphere interactions may occur as a consequence of a transition from forest to grassland.

Historical evidence suggests that two equilibria in the coupled vegetation and climate system may exist for the Sahel region of West Africa (10° N–17.5° N, 15° W–15° E) (Wang & Eltahir 2000*b*), where an extended period of drought has persisted since the 1960s (Wang & Eltahir 2000*a*). Modelling experiments (Wang & Eltahir 2000*a*) suggest that this drought represents a change from a self-sustaining wet climate equilibrium to another self-sustaining dry equilibrium (figure 4).

Initially, a SST anomaly altered precipitation in the Sahel. As a consequence, the grassland vegetation shifted

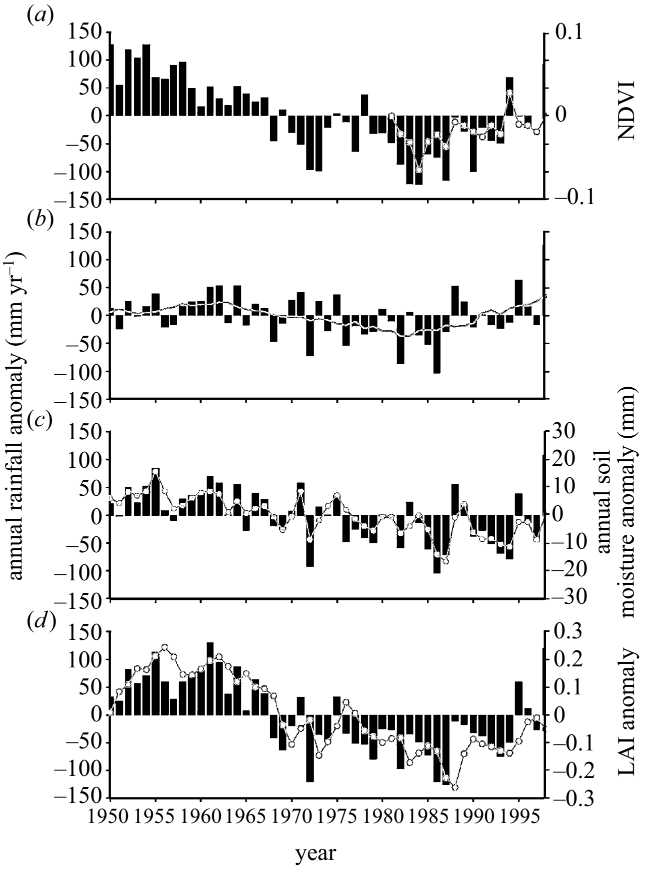

Figure 5. Annual rainfall anomaly (vertical bars) over the West African Sahel (13° N–20° N, 15° W–20° E) from 1950 to 1998. (*a*) Observed. (*b*) Model with non-interactive land surface hydrology (fixed soil moisture) and non-interactive vegetation (SST influence only, AO). Smoothed line is a 9 yr running mean showing the low-frequency variation. (*c*) Model with interactive soil moisture but non-interactive vegetation (AOL). (*d*) Model with interactive soil moisture and vegetation (AOLV). Also plotted (as connected circles, labelled on the right) are (*a*) the NDVI, (*c*) the model simulated annual soil moisture anomaly, and (*d*) the model simulated LAI anomaly. All the anomalies are computed relative to the 1950–1998 base period, except that the NDVI data are relative to 1981. (From Zeng *et al.* (1999).)

to that of a drier equilibrium state. Therefore, the combination of natural climate variability (i.e. SST anomaly), and the resulting change in land cover, were both necessary to alter the availability of moisture for the atmosphere in the longer term (figure 5) and to determine the equilibrium state (Wang & Eltahir 2000*b*).

Wang & Eltahir (2000*b*) found that vegetation is partly responsible for the low-frequency variability in the atmosphere–biosphere system characteristic of the Sahel and for the transition between equilibrium states. In the model, moist (i.e. favourable) growing seasons facilitate greater root growth of perennial grasses while dry (i.e. unfavourable) growing seasons lead to less root biomass. During subsequent years, the smaller (larger) amount of root biomass leads to less (more) above-ground growth resulting in a smaller (larger) leaf area. The smaller (larger) leaf area then transpires less (more) water to the atmosphere, providing less (more) atmospheric moisture for precipitation. This causes the atmosphere–biosphere system to remain in the drier (wetter) equilibrium.

Similar studies suggest that the monsoon circulation in West Africa is sensitive to deforestation. However, the sensitivity of the monsoon circulation to changes in land cover depends critically on the location of the change in vegetation (Zheng & Eltahir 1997). Desertification along the Saharan border has little impact on the monsoon circulation, while deforestation along the southern coast of West Africa results in a complete collapse of the monsoon circulation, with a corresponding reduction in regional rainfall (Zheng & Eltahir 1998). This illustrates that relatively small areas of land cover can determine the equilibrium state of the atmosphere–biosphere system of an entire region.

Eltahir (1996) proposes a theory to explain, in greater detail, the occurrence of multiple equilibria such as these. The theory suggests that large-scale tropical circulation depends upon a gradient in moist static energy between the boundary layer above the ocean and inland. A large (small) gradient leads to strong (weak) monsoon circulation and wet (dry) conditions in the Sahel. Perturbations in vegetation can alter the moist static energy gradient by altering total net surface radiation and also the amount of, and partitioning between, sensible and latent heat fluxes.

Similar mechanisms have been proposed for the boreal forest–tundra boundary (Levis *et al.* 1999). Levis *et al.* (1999) examined the boreal forest–tundra boundary under current climate conditions to determine if multiple stable states in the atmosphere–biosphere system are possible. In one simulation, they initialized the model with the current boreal forest–tundra boundary. In a second simulation, they initialized the model with boreal forest extended to the Arctic coast. In both simulations the atmosphere–biosphere system converges to a single state, suggesting that for current conditions there is a single stable equilibrium in the region—at least for the processes in this model and at the scale of the continent.

The simulations performed by Claussen (1998) and Kleidon *et al.* (2000) are not specifically designed to test the forest–tundra boundary. However, their results (described in more detail above) are consistent with a single stable equilibrium at the forest–tundra boundary. Some caution is needed in interpreting these results in this manner because the two experiments compared: (i) forest and desert; and (ii) forest, grassland, dark desert and light desert as opposed to the forest and tundra specifically. However, the occurrence of a single equilibrium under the different initial vegetation conditions used by each suggests that the atmosphere–biosphere system at the forest–tundra boundary is not sensitive to the vegetation initially present, at least for current conditions.

It is also important to consider that results from all such models depend on how the model aggregates over processes that can occur at smaller scales than is implicit in the simulation: e.g. local variations in soils, fire regimes, or slope and elevation variability may all be neglected. The extent to which it is necessary to account explicitly for such processes, or to which such processes might influence conclusions about stability, remain a major point of debate in all simulations that, for practical necessity, must parametrize the effects of processes occurring on small time- and space-scales. This suggests that a hierarchy of models of varying complexity (and observations to test them) is the approach most likely to determine the implications of the degree of aggregation in various models.

Additional studies suggest that at other times some regions, currently possessing a single equilibrium in the climate–biosphere system, may have undergone abrupt changes. At 6000 years before present, the Sahara was heavily vegetated, but over the next 1000–2000 years an abrupt change in vegetation and climate occurred (Claussen *et al.* 1999). In model simulations Ganopolski *et al.* (1998) found that an atmosphere–ocean–vegetation coupling was more representative of the climate of the Sahara, with the addition of vegetation increasing precipitation fourfold: a strong positive feedback between climate and vegetation distribution. Then, as orbital forcing caused a slow and steady decline in summer radiation, the Sahara abruptly underwent desertification as a consequence of interactions between the orbital changes and the atmospheric and biospheric subsystems (Claussen *et al.* 1999). These results suggest that the Sahara of the mid-Holocene period may have been prone to abrupt and irreversible changes, while currently in a single, stable equilibrium condition (i.e. desert).

Many factors complicate the interpretation of model results such as these, however. Natural variability and ecosystem disturbance—both human and natural—are often not realistically incorporated into vegetation models. Whether different modelled equilibria remain stable under the more complicated conditions of the natural world requires additional exploration for many regions. Furthermore, natural ecosystems are rarely, if ever, at equilibrium at the particular spatial and temporal scale of interest. Therefore, determining whether a particular region has multiple equilibria as opposed to an incomplete recovery from disturbance will require testing across a hierarchy of models incorporating different processes at different scales. To the extent that modelled behaviours remain insensitive to such tests, robust conclusions about complex system behaviours may be drawn with increasing confidence. Of course, the level of disturbance itself is an endogenous component of the climate–vegetation system and any change in the disturbance regime could generate new equilibria in the coupled system.

In addition, it is important to recognize that our review of multiple equilibria in the coupled climate–vegetation system is focused at the broadest scales of ecosystem structure and function as they relate to climate (e.g. albedo, transpiration and roughness). At other biological scales (e.g. genetic, species and population) different processes and characteristics may have multiple equilibria. For example, species or population extinction and loss of genetic diversity may occur without transitions in the climate system. Such changes clearly constitute different equilibria (e.g. with or without a particular species) that may be profoundly important biologically, but these different equilibria are not relevant at the scale of the climate system.

4. DISCUSSION

Anthropogenic climate change will probably alter current equilibria throughout the climate–biosphere system. In many regions of the world the current climate–biosphere system appears to reside in a single stable equilibrium (e.g. climate–biosphere interactions at the boreal forest–tundra boundary). Such regions seem capable of recovery from the perturbations that result from temporary anomalies, given sufficient time.

Even in regions currently having a single equilibrium, global changes in general and climate change in particular will cause changes in the equilibrium of the climate–biosphere system. However, if the changes in these regions are largely linear and relatively predictable, the changes that result from increasing GHG concentrations may be relatively reversible (assuming that no unforeseen thresholds are crossed and that such regions do not develop multiple equilibria as a result of those changes).

For example, the boreal forest–tundra boundary may expand into higher latitudes as temperatures increase over the next century. The rate of change would probably be relatively predictable and fairly linear (assuming relatively accurate climate prediction and accurate understanding of species migration). If so, then this new location of the forest–tundra boundary would constitute a new equilibrium but there would still only be one equilibrium for the system. Furthermore, change, in the form of this new equilibrium, would be reversible in that a return to current climate conditions would, given sufficient recovery time, lead to a return to the current climate–biosphere equilibrium (and the current forest–tundra boundary).

This is not to suggest that the changes in those regions that experience smooth and relatively slow shifts from a single equilibrium to a single new equilibrium would be benign. Indeed, such changes could constitute large perturbations to biological communities (resulting in range shifts, population or species extinctions, and changes to ecosystem structure and function) and may also dramatically impact social and economic conditions, particularly in the developing world. Moreover, even if the changes appeared smooth and reversible when aggregated over many decades and large regions—the scale of a continent for example—locally there could be abrupt changes and even complex dynamical behaviours.

Even linear and predictable changes to biological systems could dramatically influence social and economic conditions through alterations of the flow of goods and services provided by those biological systems. Such goods and services include provision of food, maintenance of the atmospheric composition, mitigation from flood and droughts, provision of pollinators for crops, decomposition of wastes, and the provision of clean water.

This line of reasoning may suggest only that more systems are coupled and at an even greater variety of scales than we consider here. The atmosphere–biosphere system may change smoothly but social and economic systems that are also coupled to the climate–biosphere system may lead to additional emergent properties. The location of the boreal forest–tundra boundary may shift predictably with concurrent shifts in ecosystem services. However, the social and economic systems dependent on the ecosystem services provided by boreal forest or tundra may not shift smoothly or predictably.

More complex are the possible changes to come in regions that currently have multiple equilibria in the climate–biosphere–economic system. Changes in these regions may be more rapid or less predictable than the changes in other regions. Furthermore, changes from one equilibrium to another may not be reversible.

Systems already possessing multiple equilibria can change state rapidly following even relatively mild or short-lived perturbations. The change from wet to dry equilibrium states in the Sahel following a brief climate anomaly in the 1960s illustrates this possibility. The results of climate changes in such regions could be felt more rapidly than in regions with a single equilibrium in that transitions occur more abruptly. Thus, even small future climate changes may require significant environmental and social adaptation if these systems are close to unknown thresholds and are consequently forced to other stable equilibria.

Societal adaptation may prove difficult as a consequence of the abrupt, unpredictable and irreversible changes that may occur as a result of climate–ecosystem dynamics. The advanced warning and slowness of transition that would accompany gradual linear changes will not apply for abrupt change. Indeed, efforts to anticipate adaptation to climate change may even prove counter-productive in regions that experience such rapid transitions between equilibria. THC collapse, for example, could occur after the North Atlantic region has made substantial efforts toward adaptation to the warming that accompanies increasing GHG concentrations. Indeed, plausible 'surprises' such as THC collapse pose a quandary to those countries or regions deciding how best to prepare and adapt to climate change. Should the North Atlantic region, for example, take steps to fully adapt to smoothly occurring warming, or hedge bets by planning for THC collapse, or aggressively attempt to mitigate GHG emissions to levels below calculated thresholds that might trigger THC collapse?

The Sahel region and the THC system of the North Atlantic are examples of current systems with the potential for multiple equilibria and abrupt nonlinear changes. As the future climate changes, the state of systems with multiple equilibria can change rapidly, and an understanding of the mechanisms by which such equilibria are reached is critical. Modelling of coupled systems across a hierarchy of approaches is a first step in this process.

Another potential complexity is the possibility that the number of equilibria within a region may change as a result of climate change. That is, regions within multiple (single) equilibria may become single (multiple) equilibrium regions under future climate changes. West Africa could cease to have multiple stable equilibria, or another region currently without multiple equilibria could acquire that condition. Furthermore, a large-scale equilibrium change like a THC collapse could cause a chain of state changes in numerous other systems, such as marine and terrestrial ecosystems and the hydrological cycle and precipitation patterns in Europe. Of course, these are only speculative possibilities, but they underscore the need to design models to account for potential nonlinear behaviour that could cause plausible state changes such as the examples discussed above.

The emergent properties of coupled models should also be considered in the policy process, since they suggest that conventional assumptions of smooth changes may not be valid for many systems, especially when rapidly forced or substantially disturbed. Abrupt changes, multiple equilibria and unpredictability, in general, retard adaptive capacity and could refocus policy attention on prevention relative to adaptation. The example of the linkage between near-term policy decisions and a future collapse of THC demonstrates the importance of taking abrupt nonlinear behaviour into account in current climate policy decisions, as it suggests that seemingly 'optimal' economic behaviour for the next few decades could precondition a catastrophic collapse of this ocean current in the 22nd century. Similarly, the Sahel example suggests that changes in aridity and subsequent effects on vegetation cover, grazing pressures and agricultural production could have significant system-scale impacts that should be considered. At the very least, the possibility of such nonlinear emergent properties of coupled socio-natural systems should widen the ranges of potential future impacts from human disturbances beyond the spans now calculated with conventional models that do not include already known nonlinear processes.

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GLOSSARY

GCM: general circulation model
GHG: greenhouse gas
GIS: Greenland–Iceland–Scotland ridge
LAI: leaf-area index
NADW: North Atlantic deep water
NDVI: normalized difference vegetation index
SCD: simple climate demonstrator
PRTP: pure rate of time preference
SST: sea-surface temperature
THC: thermohaline circulation
WBC: western boundary current