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V. A Simple Climate Model Used in Economic Studies of Global Change

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A. Taking Surprises into Account

Analysts need to do a better job of characterizing climate "surprises" – the low-probability but high-consequence scenarios – that are driving much of the international concern about climate change. Currently, most analyses rely on models or projections that assume "smooth behavior" — i.e., the climate responds slowly and predictably, gradually warming as atmospheric GHG concentrations increase. In reality, the global climate is a complex system that could behave quite erratically. The circumstances that could drive such behavior have to do with physical characteristics of the climate system itself, as well as the rate of GHG buildup.

This paper describes a climate model that is both simple enough to use in economic studies, and complex enough to explore the causes and consequences of one major type of "climate surprise" — the collapse of the "conveyor belt" circulation of the North Atlantic Ocean. This particular climate surprise is probably the best-understood and largest plausible effect of its kind. The model will enable researchers and policy makers to see more clearly the range of possible futures that could result from current policy choices.

B. Coupling of Simple Climate and Economic Models

Climate policy analysis increasingly has relied on integrated assessment models (IAMs) which couple climate models to economic models to derive "optimal" carbon abatement measures. Because of its simplicity and relative transparency, the Nordhaus (1992) Dynamic Integrated Climate Economy (DICE) model is widely used. Such IAMs often make numerous simplifying assumptions in all sub-components. This has led to a number of critical studies pointing out that alternative — but comparably plausible — sets of structural assumptions can produce very different results. In particular, researchers have studied alternative assumptions about: (1) the mechanisms and rates at which nature removes carbon from the atmosphere; (2) discount rates (which express society's preference to obtain benefits sooner and incur costs later); and (3) technology improvement.

Such optimizing IAMs determine the optimal carbon control rate by balancing the economic costs of climate policy — usually a carbon tax imposed on a perfectly functioning market economy — against the economic costs of unabated CO2 buildup. That buildup causes climate change — calculated by a simple climate sub-model — which, in turn, is assumed to create “climate damage.” Nordhaus (1992) uses only one “damage function” (i.e., the assumed mathematical relationship between the amount of climate change and the loss of economic assets associated with that level of climate change) in his DICE model. DICE is a simple energy-economy model for the aggregate world economy coupled to the comparably simple “two-box” (ocean and atmosphere) global-scale climate model of Schneider and Thompson (1981).

Even though DICE is a model with smoothly varying components (i.e., no “surprises” built in), it is still quite sensitive to assumed climate damage relationships. Roughgarden and Schneider (1999) used a probability distribution for damages to show this sensitivity. The resulting probability distributions for “optimal” carbon taxes show about a 5 percent chance that such a tax should be negative — i.e., a subsidy to fossil fuel burning. They also indicate that there is about a five percent chance that the optimal tax should be about $200 per ton carbon emitted, which would effectively eliminate burning coal, and constrict oil consumption significantly. The only difference between these radically different policies is the assumed climate damage associated with a given level of smoothly varying climate change. While the use of a probability distribution of damage functions clearly expands the range of optimal policies the model “recommends,” to date none of the many studies using DICE with alternative formulations or parameters[1] has used a climate model that produces rapid non-linear events.

The Schneider and Thompson (1981) model is capable only of smooth behavior. Smooth behavior is what most conventional analyses like DICE assume — i.e., a proportionate increase in temperature for each increment in GHG buildup, rather than abrupt or threshold climatic responses to smoothly increasing GHG concentrations. However, as noted in Houghton et al. (1996), “non linear systems when rapidly forced are subject to unexpected behavior.” A non-linear system is one in which a given increment of forcing produces disproportionate responses — such as a “flip-flop” in ocean currents, or a rapid disintegration of an ice sheet.

Therefore, the authors extended the original “C” (for “Climate”) in DICE to a new model. This new model, while retaining many of the properties of the smoothly varying 1981 Schneider/Thompson climate model, now includes mathematical relationships that allow it to mimic the behavior of complex three-dimensional coupled atmospheric and oceanic sub-models. In particular, the new model includes the rate of increase of GHG concentrations, which most current models neglect. The rate of GHG build-up may be as important a driver of climate effects as the absolute level, especially in causing climate surprises that might not otherwise have been triggered if GHG buildups were slower. Such complex models produce abrupt, non-linear behavior, in particular the collapse of the so-called “conveyor belt” circulation of the North Atlantic Ocean, when rapid GHG buildups are assumed.

The new model is designed to reproduce the climate behaviors anticipated by researchers in the climate community. The purpose here is to produce a tool that: (1) is relatively simple; (2) is capable of both exhibiting non-smooth behavior and taking into account the rate of GHG buildup; and (3) can be coupled to economic models like DICE and still be computationally efficient enough to allow many repeated simulations on modest computers. This new tool is called a Simple Climate Demonstrator (SCD), and its properties and performance are explained below.

C. The Need for an Improved Climate Model Component

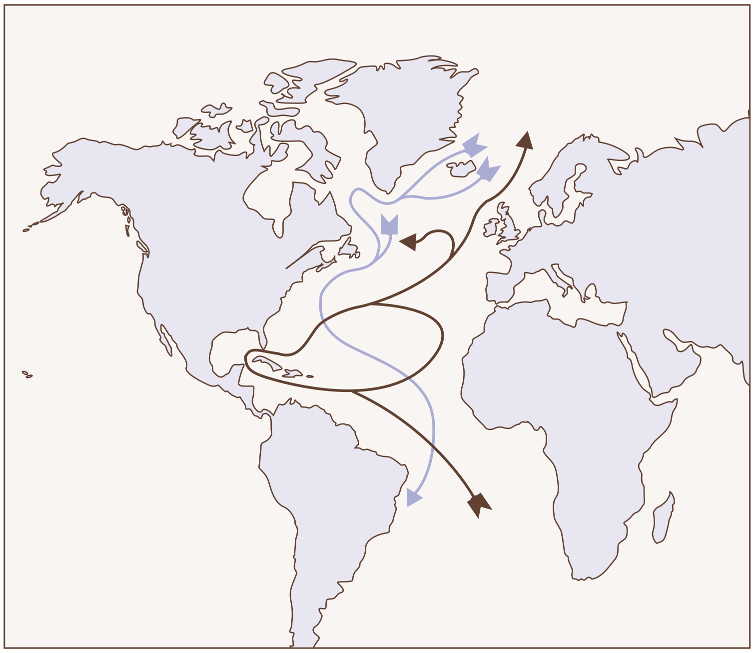
Large, three-dimensional numerical models of Earth's climate system have been the reference standards for global change research for several decades (Washington and Parkinson [1986]). In the past, most of these models have been essentially atmospheric models with grossly simplified or non-existent representations of oceans. The 1990s saw the replacement of these earlier climate models with “fully coupled” (i.e., atmospheric sub-models joined with oceanic sub-models) atmosphere-ocean models that simulate ocean currents as well as atmospheric winds to represent better the actual interactive climate system (Houghton et al. [1996]).

The addition of an interactive and circulating ocean sub-model led to some interesting model behaviors that did not occur in the older atmosphere-only simulations. The appearance of El-Niño-like variability (i.e., a large oscillation in temperatures and precipitation across the Pacific Basin associated with radical shifts in drought and flood regimes) is one example. Perhaps more importantly, the new coupled models exhibit what was once thought of primarily as a mathematical curiosity, namely the ability to have two very different stable climate states for identical forcings (Manabe and Stouffer [1988], and Rahmstorf[1995]). (Forcings are pressures put on the climate system from outside of the system. Changes in the heat output of the sun, or changes in the atmopheric concentrations of GHGs from human emissions, are examples of such "forcings." By analogy, the climate states can be likened to the two positions of a light switch (on or off), where each position is stable indefinitely unless modified by an external force (e.g., a finger pushing the switch with sufficient pressure).)

Figure 4

A Map of the North Atlantic Ocean

Thermohaline Circulation



In the case of the Earth's climate, the two stable states manifest themselves as two very different values for the strength of the overturning circulation in the Atlantic Ocean. The Gulf Stream that warms Europe is part of this circulation. This circulation, as depicted in Figure 1, is driven by the sinking of cold, dense water at high latitudes and forms part of the global ocean "conveyor belt" (Broecker [1991]). The circulation is called "thermohaline" because the density differences that drive it are determined by temperature and salinity differences. The thermohaline overturning circulation can be idealized as the sinking of dense plumes of water at high northern latitudes, followed by transport southward in the deep ocean. Upwelling at lower latitudes and return flow northward in the upper ocean complete the circuit. The two modeled stable states for this flow are: (1) similar to present day, and (2) no conveyor belt flow at all. The "no flow" case is referred to as "overturning collapse" or the "thermohaline catastrophe."

This “two-solution” behavior found in climate models would be a mere mathematical oddity if it were not for the profound influence of the Atlantic overturning circulation on climate, particularly the climate of the North Atlantic and western European region. Western Europe is up to 15ºC warmer in winter than it would be if the heat transported northward by the thermohaline overturning circulation were to cease (e.g., Schneider, Peteet and North [1987]). Moreover, the potential for thermohaline circulation collapse is not just some model artifact. The paleoclimatic record clearly shows a dozen or more incidences of reduced or collapsed thermohaline circulation. Why did the circulation collapse in the past? Scientists believe that, during glacial periods, the ice sheets partially collapsed, and discharged large amounts of freshwater into the North Atlantic in the form of massive iceberg releases (Broecker, et al., [1985] and Seidov and Maslin [1999]). Because fresh water is less dense than salt water, this fresh water formed a layer at the surface of the Atlantic that inhibited sinking and encouraged sea ice formation. The sea ice, in turn, blocked the easy transfer of heat from the ocean to the air that blows over Europe. This caused much colder than normal conditions in Northern Europe. (See Figure 1 which shows the locations of the thermohaline circulation centers.)

Although the circulation collapsed during cold climates in the past, this history is still highly relevant to a much warmer future. Any process that acts to lessen the density of the northern Atlantic Ocean can reduce or even collapse the overturning circulation. Freshwater has contributed to these changes during the most recent glacial period. Massive freshwater input from collapsing ice sheets cannot occur today since the glacial age ice sheets are gone, but increasing temperature and precipitation from global warming may be another trigger for thermohaline collapse.

Warming directly reduces the density of surface oceanic waters, thereby causing a reduction in sinking potential. In addition, warming could result in atmospheric storms transporting more fresh water to the North Atlantic from enhanced evaporation in lower latitudes. Either process (direct warming, or injection of fresh water) would slow down both the sinking rate of cold water in the north, and the rate at which surface currents of waters from the south bring warm, salty water towards higher latitudes (e.g., the Gulf Stream in the case of the North Atlantic-see Figure 1). Because north-south temperature *differences* drive the transport of southern waters north, extra greenhouse heating in the north would reduce the northward flow of warm Gulf Stream waters. This reduction in warm inflow would serve as a stabilizing negative feedback on the reduced circulation resulting from the initial warming. In other words, the reduction in the thermohaline circulation tends to be self-limiting. A circulation reduction allows the system to cool down, recreate dense surface waters, and thus maintain the sinking. At the same time, however, reducing the strength of the Gulf Stream from either a warming or a freshening of northern surface waters would reduce the flow of salty subtropical water into the North Atlantic. This would reduce the salinity of the water, and thus further reduce cold water sinking, thereby serving as a destabilizing or positive feedback on the reduced overturning rate. The rate at which the system is pushed could determine whether the positive or negative feedbacks dominate, and control whether the thermohaline catastrophe occurs.

Climate modelers now understand the importance of correctly simulating ocean circulation in their models. Current comprehensive models differ not only in their overall climate sensitivity, but also in how well they simulate the present-day thermohaline circulation and its response to global warming scenarios (Rahmstorf [1999]). Researchers developed simple climate models two decades ago (e.g., Schneider and Thompson [1981]) to aid in understanding the climate system, to explore transient (i.e., time-evolving) responses, and to facilitate coupling to other models, such as economic models. Further developments of such models have lagged behind in including the “on/off switch” non-linearities that are also called “surprise” scenarios (e.g., Houghton et al., [1996]).

A goal for this study is to develop a “next-generation” simple climate model that would demonstrate behaviors similar to those found in much more complex models; hence the name “Simple Climate Demonstrator,” or SCD. Primary objectives are that the model be simple enough to understand thoroughly, and computationally efficient enough to be useful for coupling to similarly simplified economic models.

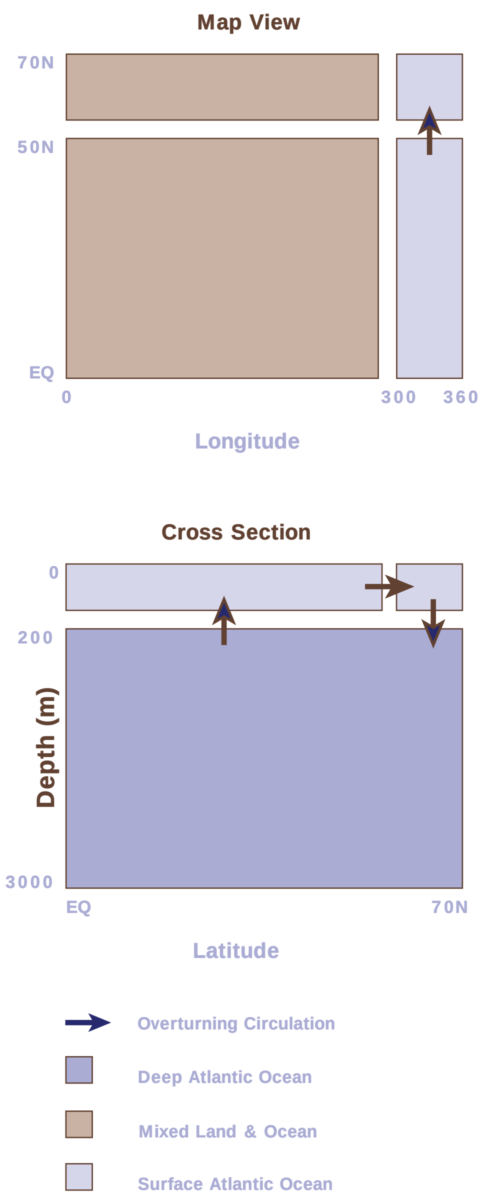
D. The Simple Climate Demonstrator Model

The SCD model represents the world as five geographic regions, or boxes, in the Northern Hemisphere (see Figure 2). Thus the authors assume a priori that the qualitative features of the climate system of interest can be reproduced with only the Northern Hemisphere. The fundamental properties of the boxes are their size, location and connectivity. As shown in Figure 2, there are four surface boxes and one deep ocean box.

The two Atlantic sector surface boxes represent an idealized ocean 60º of longitude wide extending from the equator to 70º north (70N). This is a rough approximation of the geographic extent of the actual north Atlantic. The other two surface boxes represent the mixture of land and ocean that is “non-Atlantic” and are 300º of longitude wide. The latitude range of the northern boxes, 50N to 70N, is chosen to approximate the location of deep-water formation in the North Atlantic. The boxes of the SCD model are connected by flows of thermal energy and freshwater (or salinity). A modeled thermohaline overturning circulation connects the three ocean boxes. A further description of the SCD model is contained in the Appendix.

Figure 5

The **Simple Climate Demonstrator** (SCD) Model



Numerous tests were done to characterize the response of the model to changes in climate forcing. As found in other models, SCD exhibits two stable states. One state has a substantial overturning circulation of about 20 Sverdrups (1 Sverdrup = 1Sv = one million cubic meters of seawater per second). The second state has no overturning. Lowering the density of the water in the northern upper ocean box can trigger a jump from the overturning to the no-overturning state. This can be accomplished by increasing either the temperature or the amount of freshwater injected, both of which are likely to occur with increasing CO_2. To move from the no-overturning collapsed state back to a “normal” circulation requires a large decrease in global temperature, or a large increase in salinity. The model produces a temporary, or transient, thermohaline circulation reduction or permanent collapse if the salinity of the northern upper ocean box is perturbed in a way that mimics a massive freshwater input from melting icebergs. Since the SCD model is designed to behave in this way, its ability to replicate this paleoclimatic history is comforting, but not definitive. More work will need to be done to see if the paleoclimatic record of the North Atlantic can be used to ensure that the SCD takes past climate behavior into account even more precisely (see Rahmstorf and Ganopolski [1999], for further discussions).

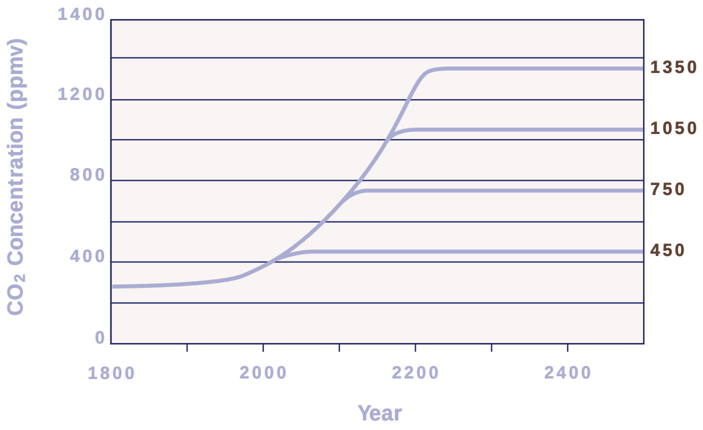
E. Global Warming Applications

1. Varying the CO_2 Stabilization Concentration

The SCD model was used to simulate global climate change from pre-industrial atmospheric concentrations of about 280 parts per million by volume (ppmv) CO_2 (current concentrations are about 370 ppmv) for the years 1800 AD to 2500 AD for four atmospheric CO_2 scenarios, as shown in Figure 3. In each case the CO_2 concentration follows the historical curve until 2000 AD. After 2000 AD, the concentration follows an approximation of the IPCC IS92a “Business as Usual” (BAU) curve, which effectively has a 0.61 percent per year exponential growth rate. The curves depart from the BAU exponential growth and stabilize at the arbitrary values of 450, 750, 1050, and 1350 parts per million (ppmv). (The values of 450 and 750 ppmv have often been used to provide a plausible range of stabilization concentrations. However, larger atmospheric concentrations are expected for 2150 AD and beyond, unless there is a significant shift away from fossil fuel-based energy systems, a major improvement in

Figure 6

CO_2 **Stabilization Scenarios** Used in the SCD Model



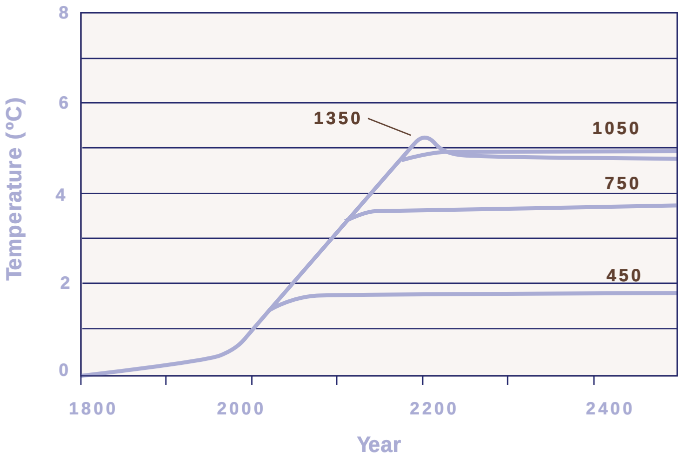
*Four time-dependent atmospheric CO_2 concentration scenarios used in the SCD model. Each starts with the historical CO_2 increase to the present day, then moves into the future following the IPCC IS92a scenario. The effective exponential CO_2 increase rate after the year 2000 is 0.61% per year. Each scenario falls away from the exponential increase and stabilizes at the value shown.

energy efficiency, or massive carbon sequestration[2] programs implemented over the next 50 to 100 years (e.g., Hoffert et al.,. [1998].) Even stabilizing CO_2 *emissions* sometime late in the twenty-first century at twice the present levels would lead to a century of more growth in CO_2 concentrations, which would stabilize in the twenty-second century at well above a doubling of present *concentrations*. Thus, the higher values of 1050 and 1350 ppmv are quite plausible scenarios as well, even though it is often assumed that humans would act to curb CO_2 emissions before such high concentration levels were reached. The model was run with a global climate sensitivity of 3.0 ºC (i.e., a 3.0 ºC global surface air temperature warming for an equilibrium[3] doubling of CO_2 concentrations). This sensitivity is in the middle of the IPCC range of 1.5 ºC to 4.5 ºC (Houghton et al., [1996]).

The global mean surface temperature change and the ocean circulation overturning strength are shown in Figures 4 and 5, respectively. The temperature response is straightforward except in the case of the highest CO_2 concentration. In this case, the temperature displays anomalous behavior at year 2200 and actually decreases below that of the next highest CO_2 concentration case (i.e., 1050 ppmv). The cause of the global temperature behavior can be found in the ocean circulation overturning strength (Figure 5). In the lower CO_2 concentration cases, increasing CO_2 causes the overturning to weaken temporarily. The overturning then slowly recovers to near 20 Sv as the time-dependent temperature and salinity perturbations fade after several thousand years of stabilized CO_2 concentrations (not shown).

Figure 7

Global Mean **Temperature Response**

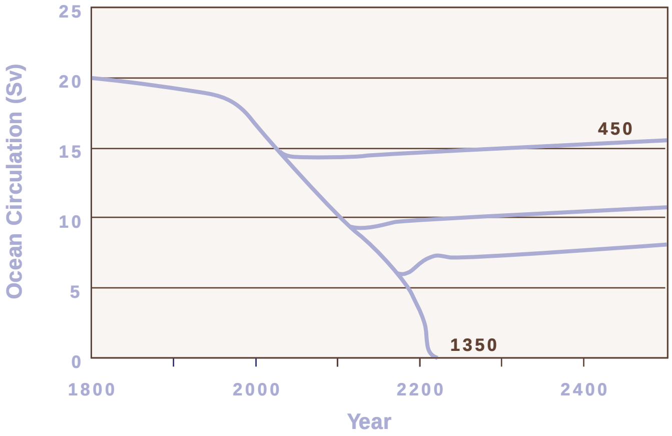


Note: Global average surface temperature change from the SCD model given the four CO_2 scenarios in Figure 5. In these cases, the model's climate sensitivity is 3.0ºC (i.e., a global mean increase of 3ºC for a climate in long-term equilibrium with doubled CO_2). Note that stabilizing at 1350 ppmv produces an anomalous cooling of the global temperature as a result of the collapse of the North Atlantic thermohaline overturning circulation.

In the highest CO_2 concentration case, the overturning circulation collapses permanently, as opposed to merely slowing down. The overturning collapse causes a loss of heat transport to the north ocean surface box, which then cools substantially. This northern cooling increases snow cover and sea ice, thus actually reducing the global mean temperature compared to what it would be without the overturning collapse.

Figure 8

North Atlantic Overturning Circulation Response



Note: Response of the North Atlantic overturning circulation strength for the four CO_2 scenarios shown in Figure 5. The present circulation strength is thought to be roughly 20 Sverdrups (Sv), where one Sv is defined as a million cubic meters per second. The strength of the overturning circulation decreases with increasing CO_2 until a point is reached where the overturning ceases entirely (the so-called thermohaline catastrophe).

The model was tested to see if reducing the CO_2 concentrations back toward pre-industrial levels could force the collapsed circulation back to “normal.” The model showed that the CO_2 concentration would have to be reduced to around 100 ppmv to accomplish this. This value is probably lower than has ever occurred on Earth, and is not likely to be photosynthetically acceptable for natural ecosystems and agriculture, even if it were physically possible to attain. An emergency reduction of the atmospheric CO_2 concentration is an unlikely remedy for reversing a thermohaline catastrophe once it occurs, given such non-linear, hysteresis behavior. (Hysteresis means that a system forced to change will not be restored to its previous state when that forcing is removed, but that an additional forcing in the opposite direction to the original forcing is needed to restore the system to its original state.)

The temperature response of the northern upper ocean box is very different depending on whether the overturning circulation collapses or not. This is as expected, and it agrees qualitatively with paleoclimatic observations and with several available simulations of this event (i.e., Schneider, Peteet, and North[1987] and Rahmstorf and Ganopolski, [1999]). After a thermohaline collapse, the north ocean box stabilizes at a temperature that is colder than the present day by about 8 ºC, even though the globe as a whole warms by 3.6 ºC. This would lead to the seemingly self-contradictory condition in which the world warms well beyond the range experienced over the past 10,000 years — the era during which human civilization evolved — while the North Atlantic, and quite possibly much of Northern Europe could cool. Such an event would clearly require *revisiting the smoothly varying climate damage functions* typically used in current generations of IAMs.

2. Varying the Climate Sensitivity

The actual sensitivity of the Earth's climate to CO_2 is unknown, but generally thought likely to be in the range of 1.5 to 4.5 ºC per CO_2 concentration doubling in equilibrium. However, many scientists assign subjective probabilities of some ten percent to the possibility of climate sensitivity being outside (either greater or lower than) this range (e.g., Morgan and Keith [1995]). To test the dependence of the model's circulation response to its climate sensitivity, four simulations were performed with climate sensitivities of 1.5 ºC, 2.25 ºC, 3.0 ºC, and 4.5 ºC per CO_2 doubling. Each case uses the same CO_2 scenario, namely the 750-ppmv-stabilization case shown in Figure 3.

The ocean circulation temporarily slows by 25 percent to 50 percent in the cases having the three lowest sensitivities. The ocean circulation collapses at the highest climate sensitivity used here. In the case with circulation collapsing, neither the CO_2 stabilization value (750 ppmv) nor the high climate sensitivity (4.5 ºC) is implausible, although the climate sensitivity is near its generally accepted upper limit. In future simulations it would be more appropriate to use subjective probability distributions for all feasible parameters, including climate sensitivity and CO_2 concentration stabilization levels (see, for example, Schneider [1997]).

3. Varying the Present-Day Overturning Rate

Just as comprehensive climate models have different sensitivities to CO_2 increase, they also have varying rates of thermohaline overturning circulation in their unperturbed, present-day “control” cases (Rahmstorf [1999]). Scientists are uncomfortably uncertain about the detailed geographic locations and even the overall average strength of the present day overturning. Current comprehensive models produce “control” circulations varying from 10 Sv to over 40 Sv in the average strength of overturning. It seems plausible that a model with a stronger present-day circulation would be less prone to a circulation collapse than one having a weak present-day circulation since the stronger the initial circulation, the more flexibility it has to change before reaching the instability point. By analogy, if an object were left on a table that was often getting bumped, the object would be more likely to fall off if it started out closer to the edge of the table than to the middle. To test this hypothesis, the SCD model was adjusted to create a "strong" control case having 40 Sv of overturning and a "weak" control case having only 10 Sv. All else was kept the same. The 750 ppmv CO_2 stabilization scenario was then run for the four climate sensitivities of 1.5ºC, 2.25ºC, 3.0ºC, and 4.5ºC per CO_2 doubling.

As conjectured, the "strong" overturning model version does not show a collapse even for the highest climate sensitivity (4.5 ºC), but the "weak" version shows a collapse for both the 4.5 ºC and 3.0 ºC climate sensitivity cases.

This result indicates that the modeler's assumption regarding the present day overturning rate is probably an important factor in the model's sensitivity to thermohaline collapse (e.g., Rahmstorf [1999]). Variation in the assumed initial overturning rate, combined with variations in the model's climate sensitivity, probably explains much of the differences in sensitivity to thermohaline collapse found among models. Furthermore, there is yet a third geophysical process that introduces further uncertainty, but which we have not considered in the SCD: hydrological sensitivity (see Rahmstorf and Ganopolski [1999]), which is the amount of fresh water transported via the atmosphere to the North Atlantic from water that evaporated in more tropical latitudes as a result of the world warming.

4. Varying the Rate of Increase in the Concentration of CO_2 in the Atmosphere

Some models show that the rate of increase of CO_2, not just the absolute amount, can influence thermohaline collapse (e.g., Stocker and Schmittner [1997]). The reason that the rate matters is that the northern ocean can rid itself of lower density surface water by pumping it into the deep ocean, thus effectively diluting the perturbation, but only if the density perturbation is slow enough. That is, if the ocean is disturbed suddenly by freshwater input or rapid warming, there is less time for the saltier or warmer water to mix with the rest of the ocean water than is the case for slow disturbances. Thus, the sudden disturbance will have more impact on the reduction of overturning than a more slowly building disturbance, even if both disturbances eventually represent the same cumulative amount of fresh water injection.

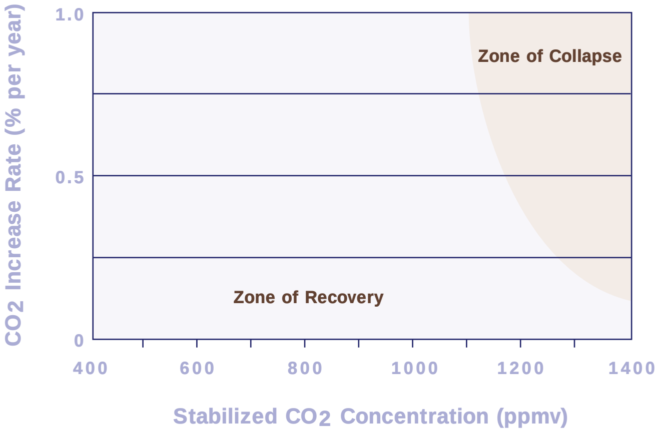
Earlier it was noted that there are two opposing feedback effects when the circulation weakens: a stabilizing (negative feedback) thermal effect and a destabilizing (positive feedback) haline (salt) effect.

If the forcing on the system is rapid enough, it appears that the positive feedback dominates and the catastrophe is more probable. That is, if temperature or fresh water input increases too rapidly, the overturning circulation collapses. However, Stouffer and Manabe (1999) found that if CO_2 is stabilized at a doubling of the present concentration (thereby preventing the total collapse of the circulation), the long-term amount of circulation weakening can actually be larger in cases of slow CO_2 build-up than in cases of rapid CO_2 build-up. This is because when CO_2 build-up is faster, even though the ocean circulation weakens more rapidly initially, the climate system is exposed for a longer period of time to CO_2 forcing in the slow doubling case. The key issue is not just the rate of build-up, but whether the stabilized CO_2 concentration, combined with the rate of increase in concentration, causes a total collapse of the circulation. In the case of a total collapse, even a return to present concentrations might not return the circulation to present-day conditions.

Fig. 6 shows a plot of the behavior of the thermohaline circulation after it is allowed to reach its equilibrium many centuries in the future as a function of both stabilized CO_2 concentrations and the annual rate of increase of CO_2 prior to stabilization. A mid-value of climate sensitivity of 3.0 ºC per CO_2 doubling was used. Each of the 420 SCD model simulations that comprise the figure was run for 10,000 years to eliminate temporary reductions in the thermohaline circulation. In this case the important question is whether the circulation collapses permanently or recovers. As can be seen on Figure 6, the stability of the circulation does depend on the rate of CO_2 increase as well as the stabilized CO2 concentration. For a CO_2 increase rate of 0.9 percent per year, the circulation collapses at 1125 ppmv. However, a stabilized concentration of 1450 ppmv can be reached without collapsing the circulation, if the CO_2 increase rate is only 0.2 percent per year. (Recall that the current rate of increase in the CO_2 concentration is 0.6 percent per year.)

Figure 9

The Ocean Circulation Zone of Collapse

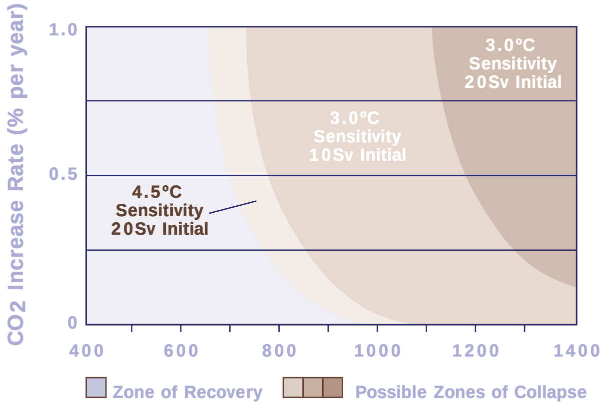


Note: The strength of the thermohaline overturning circulation is shown as a function of the stabilized CO_2 concentration and CO_2 annual increase rate. All runs start from an equilibrated pre-industrial state, follow the historical CO_2 increase, and then follow the path defined by the given increase rate and stabilization value. The model climate sensitivity is set at 3.0ºC for a CO_2 doubling. Note the permanent thermohaline circulation collapse ("Zone of Collapse") for a combination of sufficiently high stabilized CO_2 and CO_2 increase rate.

Increasing the climate sensitivity or decreasing the initial amount of overturning both act to increase the likelihood that the model's overturning circulation will collapse. This is illustrated in Figure 7, which shows how the “Zone of Collapse” enlarges. It is important to observe that the location of the dividing line between the “Collapse” and “Recovery” zones is determined by two uncertain socio-economic factors (CO$_2$ stabilization value and CO$_2$ rate of increase) and two uncertain geophysical factors (climate sensitivity and present-day ocean overturning circulation strength), and that no one is yet able to confidently place a “You Are Here” marker on this particular chart.

Figure 10

Uncertainty in the **Zone of Collapse**



Note: The dividing line between circulation recovery ("Zone of Recovery") and permanent collapse ("Possible Zones of Collapse") depends not only on the geopolitical factors of stabilized CO$_2$ concentration and CO$_2$ increase rate, but on the uncertain geophysical factors of global climate sensitivity and present-day (initial) ocean circulation overturning rate.

These calculations are not meant to be taken literally given the high degree of simplifications in the model relative to the rich set of non-linear behaviors the model shows are plausible. However, even this simple model demonstrates that complex properties of the coupled climate-economy system must be taken into account, even if the specific numbers here are just illustrative. The complexity of the system gives rise not only to large uncertainties but also to abrupt and potentially major climatic changes. This cannot be ignored by rational analysis, and is the reason to explore these possibilities with quantitative models even if specific results are not definitive.

F. What difference does the new modeling approach make in terms of policy analysis?

As noted earlier, most conventional climate-economy models used for climate policy analysis assume either fixed changes in climate forcing (e.g., a doubling of CO$_2$), or smoothly varying climate change scenarios (e.g., 0.2°C warming per decade). This paper reiterates that the climate system is non-linear, which means that thresholds may exist at certain stages in the evolution of climatic changes. At these thresholds, a smoothly varying disturbance, such as a GHG buildup, may trigger a rapid event or events. Most analysts who attempt to project the damage that climate change might bring to the environment or to society argue that human capacity to adapt can ameliorate such damages (e.g., Mendelsohn et al., [2000]). However, those analysts typically assume either fixed or smoothly varying climate scenarios. In the case of rapid climate changes, adaptive agents would have neither the knowledge of impending warming, nor the time to marshal the resources to adapt (e.g., Schneider, Easterling, and Mearns [2000]). Thus, it is likely that most analysts using smoothly varying climate changes have overestimated human capacity to adapt to rapid climate changes. Also, natural systems rarely can adapt, without losses, to rapid changes. Thus a new generation of IAMs is needed to explore the implications of rapid climate changes on managed and unmanaged systems.

Moreover, modest climate policies that may be “optimal” for smoothly varying climate change scenarios in which adaptation plays a major role may not make sense in a rapidly changing world. Much more may be at stake in reducing the rate at which humans disturb the climatic system than may be inferred from studies that assume smoothly varying scenarios — e.g., DICE and an entire generation of conventional climate-economy optimization models. The present study clearly demonstrates that a great deal of caution needs to accompany most conventional climate policy analyses in which the only cases analyzed are perfectly foreseen and smoothly increasing temperatures.

G. Conclusions

The authors have produced a simple, portable, and efficient climate model that reproduces some of the important behaviors of the comprehensive, coupled ocean-atmosphere models that currently serve as the standards for global climate research. In particular, the Atlantic overturning circulation in the simplified model and the comprehensive models responds similarly — both qualitatively and quantitatively — to time-dependent global warming forcing. This is true for both temporary reductions in the overturning circulation and for total circulation collapse. The simplicity of the model allows it to clearly distinguish the roles of four uncertain parameters in controlling an overturning collapse: (1) the CO_2 stabilization concentration, (2) the rate of increase in the CO_2 concentration, (3) the global climate sensitivity, and (4) the initial overturning circulation strength. The first two are primarily driven by socio-economic factors, controlled by human population, affluence, energy efficiency, and the technologies used to produce energy or sequester carbon. These socio-economic factors can be manipulated by the kinds of climate policies that fill the current literature and are featured in political debates. The second two factors are geophysical properties of the climate system. Although much is known about them, they still are best characterized by subjective probability distributions that allow a rather wide range of values. This range encompasses the possibilities that the conveyor belt circulation could be either highly stable or easily pushed to a catastrophic collapse. Moreover, it could take decades of empirical and theoretical research to narrow the range significantly (see e.g., IPCC Third Assessment Report, in preparation). There is a possibility that decisions made over the next few decades about GHG emission trajectories over the next century could cause an irreversible drift towards the collapse of the circulation — an event that would become part of the legacy of the twenty-first to the citizens and ecosystems of the twenty-second century and beyond.

The actual dependence of climate change on the rate at which GHGs are allowed to build up stands in contrast to the standard assumptions in most IAMs for which only the stabilization level matters, not the rate at which stabilization is achieved. This disconnect could have a marked impact on the "timing debate" (e.g., Wigley, Richels, and Edmonds [1996]) in which some argue that delayed abatement is preferable because early abatement is too costly. If the rate of GHG build-up in the nearer-term could trigger non-linearities appearing only later on in the climate system, then early abatement may be preferable (see e.g., Schneider [1997]).

Apart from its ability to emulate circulation response in a physically plausible way, the model described here is just a traditional, low-resolution, energy-balance climate model. The model is simple enough to be transparent to climate analysts but has enough adjustable parameters to mimic a range of behaviors of more sophisticated models — which can be relatively opaque to all but a few climate modelers. Given that the SCD's range of behavior is more extensive than older simple climate models, it should prove enlightening to couple this new model to economic models of similar complexity. Preliminary analyses (Mastrandrea and Schneider, in preparation) in which the SCD model presented here is coupled to the DICE model show that near-term emissions could trigger abrupt climate changes in the twenty-second century. Thus, agents with infinite foresight would adjust their current optimal CO_2 emissions control rates based on the potential severity of these far-off abrupt changes. Of course, very high discount rates cause little additional near-term policy response from twenty-second century thermohaline collapse relative to lower discount rates, yet the choice of discount rate is not only a technical option, but also a normative judgment about the value of present versus future interests.

Most conventional energy-economy models are based on smoothly varying scenarios; they do not consider rapid changes or threshold events. They likely overestimate the capacity of humans to adapt to climatic change and underestimate the optimal control rate for GHG emissions. It is critical that the full range of plausible climatic states becomes part of climate policy analysis. Indeed, to ignore the implications of rapid, non-linear climatic changes or surprises would lead to inadequate responses to the advent or prospect of climatic changes.

Endnotes

1 Parameters are the specific numerical relationships in the models.

2 Sequestration means storing carbon, for example, by planting trees, changing agricultural practices, or through yet-to-be invented techniques such as burial of carbon in deep geological caverns or at the ocean bottom.

3 Equilibrium is the situation in which the CO_2 concentration stabilizes, the climate change has gone through its transient phase, and a new steady state is achieved.

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Appendix B: Simple Climate Demonstrator Model Description

The SCD model represents the world as five boxes in the Northern Hemisphere (Figure 2). In fact, only three Atlantic Ocean boxes are required to produce a description of the north Atlantic overturning circulation. However, the additional two boxes represent the “non-Atlantic” remainder of the Northern Hemisphere. These additional boxes allow for east-west gradients and thus allow the simulated variables in each box to bear some quantitative resemblance to real world values, as opposed to being a more

qualitative representation of an idealized system. Even more realism could be added by extending the model to have a southern hemispheric component or by sub-dividing the boxes into land and oceanic domains. However, the more complex the system, the less easily can it be coupled to economic models for repeated runs.

The boxes of the SCD model are connected by flows of thermal energy and freshwater (or salinity). An advective (i.e., flowing horizontally between boxes) thermohaline overturning circulation connects the three ocean boxes. All other transports of heat, freshwater or salinity occur by simple “down-gradient” (i.e., from higher to lower values) linear diffusion with coefficients chosen to produce an acceptable control climate. Solar radiative heating and outgoing infrared radiative cooling are handled in the manner of numerous simple energy balance climate models (e.g., Schneider and Thompson, 1981). Outgoing infrared radiation (heat) is a linear function of the surface temperature. The proportionality factor can be adjusted within limits to control the model's overall temperature sensitivity to changes in radiative heating (i.e., to adjust the climate sensitivity of the model). The model includes a traditional snow-ice albedo (surface reflectivity) feedback that linearly increases planetary albedo as a function of decreasing temperature. This is effective only below a threshold temperature. In the simulations discussed in this report the albedo feedback (i.e., the warming-induced melting of snow or ice which enhances the warming by decreasing the albedo) only operates in the northern surface boxes because that is where the bulk of the landmasses are located. The effect of CO_2 as a GHG is added as a radiative heating logarithmically proportional to CO_2 amount. In other words, additional increments of CO_2 yield diminishing returns, as has been known for decades and included in all climate models since the 1960s.

Water is assumed to evaporate from the surface ocean boxes at a rate proportional to the saturation vapor pressure (the amount of water vapor the air can hold before condensation occurs). Thus, evaporation is a nonlinear function of temperature only. Water vapor is moved down gradient from the warmer southern ocean box to the cooler northern ocean box and precipitated, producing a positive difference of precipitation minus evaporation (P-E) in the northern box, as is observed in the actual climate system. The poleward transport of water vapor is adjusted to make the P-E values comparable to observed estimates. There is no evaporation, precipitation or runoff in the “non-Atlantic” surface boxes.

The seawater density in the three ocean boxes is determined by an equation of state that is linearized in both temperature and salinity. The strength of the thermohaline circulation is assumed to be linearly proportional to the density difference between the northern surface ocean and the deep ocean. The modeler adjusts the proportionality constant to achieve the desired circulation strength.

The various parameters of the model were chosen to produce a control state similar to that observed in the present day. In particular, the strength of the thermohaline overturning was set arbitrarily at 20 Sv (1 Sv = 1 Sverdrup, defined as one million cubic meters per second). The strength of the albedo feedback was adjusted so that the model's normal climate sensitivity to CO_2-doubling increased from 2.2 ºC per CO_2 doubling without albedo feedback to 3.0 ºC with albedo feedback. The control case equilibrium was derived by running the model for 20,000 years with a pre-industrial atmospheric CO_2 value of 280 parts per million (ppmv).

Temperatures in the control case are 16 ºC for the global surface mean, 6 ºC for the northern surface Atlantic box and 6.5 ºC for the deep ocean. The deep ocean is warmer than observed because the low spatial resolution of the model precludes the deep-water formation in cold spots of limited area that occurs in reality. Tuning the model to make the deep water colder would not affect the model's qualitative behavior, but would result in an unreasonably cold overall northern ocean surface temperature.