

Prospects for Global Warming: Controllability and observability for a coupled climate model with carbon-cycle feedbacks

Key words: global warming, carbon-cycle feedbacks, controllability, observability

MOTIVATION

Decades of research into the phenomenon of global warming have brought us step by step closer to piecing together a fully integrated Earth model. While there exists ongoing debate on several issues of global warming, there are few who question the potential impacts of this effect. It is one of the grave dangers facing mankind, which has the capacity to fundamentally challenge our current way of life on a global scale. Research to date has led us to the cusp of integrating our present understanding. The complexity and dynamics of the integrated model require a control systems analysis approach.

LITERATURE REVIEW

It was established in the late nineteenth century that carbon, specifically CO₂, is a significant factor in regulating the temperature of the earth¹. Study of ice cores, dating to 420,000 years ago, reveals that although Earth's temperature can change substantially without noticeable change in carbon levels, but if CO₂ levels do change then there appears to be a necessary effect on the temperature². Further study of the ice cores indicate atmospheric carbon proportions have been steadily increasing since the Industrial Revolution and that this rate is faster than any other increase recorded over the past 420,000 years³.

Earth has a natural carbon-cycle, in which carbon in the atmosphere exchanges with the oceans and terrestrial ecosystems. This means that higher atmospheric concentrations of carbon can be sequestered into various reservoirs located in the oceans and soil. The ocean is by far the greatest storage for carbon, storing roughly fifty times that of the atmosphere. A small fraction of the carbon in the ocean, roughly 2%, is dissolved straight from the atmosphere into surface water creating a weak acid, leading to bicarbonate. The remaining concentration of carbon is found 300 meters below the ocean surface. At this depth, water cannot exchange carbon directly with the atmosphere; instead, it receives carbon through three indirect processes. The "solubility pump" sequesters carbon through the colder, saline waters of the Arctic and Antarctic which absorb greater amounts of carbon and then sink beneath warmer waters. The carbon sequestered in this manner is confined to a global circulation belt until the water eventually resurfaces, which can take decades to centuries⁴. In the "biological pump", phytoplankton photosynthesis reduces carbon in the oceans, which in turn promotes absorption of CO₂ from the atmosphere. Finally, sinking CaCO₃ shells from biological systems transfer carbon to the lower ocean through the "carbonate pump". Although the majority of human derived carbon is absorbed into the ocean, terrestrial systems account for three times the carbon storage of the atmosphere. The carbon can be sequestered in living biomass as well as soil and decomposing biomass.

Each of the reservoirs in the Earth's carbon-cycle is limited in the amount and rate at which it can store excess anthropogenic carbon. The formation of carbonate in the oceans depends on cations supplied by weathering of rocks. Terrestrial sequestering depends on the presence of other necessary nutrients for plant growth, such as nitrogen⁴. These nutrients belong to their own cycles – each of which humans have impacted. Not only are these processes affected by the availability of key reactants, but they are also sensitive to temperature^{5,6}. The dependence of climate on CO₂ and the absorption of carbon on climate creates a feedback loop⁷.

Numerical analysis using the HadCM3 coupled ocean-atmosphere model⁸, coupled with an ocean carbon-cycle model (HadOCC) and a global vegetation model (TRIFFID)⁹ illustrates that the existence of this feedback loop weakens the strength of the carbon reservoirs, leading to a faster accumulation of carbon in the atmosphere. Moreover, simulations employing feedback in the model create a closer match to the recorded climate data than non-feedback simulations. Integration of the current reservoir models with atmospheric and climate models clearly demonstrates that a feedback approach is necessary for a complete global carbon cycle model. It is critical to understand and characterize this coupled feedback system.

PROPOSAL

It is in light of these recent findings that a systems analysis be considered for understanding the climate/carbon feedback system. Simulation models, although still rough, have been able to recreate the observed trend of carbon in Earth's atmosphere following the Industrial Revolution. Control system methods have yet to be applied to the dynamics of these coupled models. I propose to investigate the dynamics of the combined nonlinear system for the climate/carbon feedback system. Choosing viable inputs and outputs, I will analyze the system for controllability, observability, and possible control strategies. It is difficult to predict the conclusions of this study; however, the implications have the possibility of great import. If we find that the entire system is controllable through a particular variable, say the carbon transport due to the solubility pump, we may be able to take a more educated proactive role in the stabilization of our planet's atmosphere. This proposal is also of great scholarly interest due to the challenging complexity of the system. It is possible that stability arguments or control schemes will need to be adapted to fit the system. Findings will also give the climate research community a new, unique perspective to view their own results. In closing, research has shown that feedbacks are necessary to accurately model the climate/carbon system. A control systems analysis of the global warming scenario may reveal new insights into the nature of the dynamics and possibly techniques to stabilize the carbon concentrations in Earth's atmosphere.

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