A robust sequential CO₂ emissions strategy based on optimal control of atmospheric CO₂ concentrations

Andrew J. Jarvis · Peter C. Young · David T. Leedal · Arun Chotai

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Abstract This paper formally introduces the concept of mitigation as a stochastic control problem. This is illustrated by applying a digital state variable feedback control approach known as Non-Minimum State Space (NMSS) control to the problem of specifying carbon emissions to control atmospheric CO₂ concentrations in the presence of uncertainty. It is shown that the control approach naturally lends itself to integrating both anticipatory and reflexive mitigation strategies within a single unified framework. The framework explicitly considers the closed-loop nature of climate mitigation, and employs a policy orientated optimisation procedure to specify the properties of this closed-loop system. The product of this exercise is a control law that is suitably conditioned to regulate atmospheric CO₂ concentrations through assimilating online information within a 25-year review cycle framework. It is shown that the optimal control law is also robust when faced with significant levels of uncertainty about the functioning of the global carbon cycle.

1 Introduction

Any action that regulates an aspect of global climate is, by definition, attributable to a global scale control mechanism. Most commonly, these mechanisms are manifest as the natural feedback processes which act to oppose disturbance, hence contributing to the generally equable state of the surface conditions on Earth. Recently however, when faced with the prospect of a self imposed disturbance on global climate, humans have begun considering an active regulation of the climate system through the judicious release of greenhouse gases. If implemented, this behaviour will also be a global scale control mechanism, although it will differ from its natural counterparts in that the outcome would (ideally) be achieved more by way of design.
Through linking climate responses to the anthropogenic greenhouse gas emissions that caused them, climate mitigation measures effectively set up closed-loop systems comprised of the environmental sub-system(s) linking emissions to climate and the socio-economic feedback sub-system(s) that link climate to emissions (see Fig. 1). As in all feedback control, these closed-loop systems will have a set of emergent dynamic properties that differ significantly from the dynamic properties of their component parts. Therefore, the properties of the socio-economic sub-system(s) need to be specified such that the closed-loop system behaves as required. For example, an integrated assessment of this closed-loop system might attempt to specify levels of carbon taxation to modulate emissions in response to, or avoidance of, climate induced damages, such that the closed-loop system behaves in some sense optimally (Nordhaus 1991). Although not explicitly coined in these terms, this is in effect a form of optimal control system design, a branch of systems engineering that is in fairly widespread use in many areas of engineering, natural and social science, including economics, under the general heading of control theory (e.g. Richardson 1991). Indeed, Fiddaman (2002) acknowledged this fact and utilised simple empirical control elements within his integrated assessment of the climate–economy system.

More generally, control systems design focuses on the design and analysis of feedback control systems from a dynamic systems perspective. This discipline has a long and distinguished pedigree and impacts on contemporary society in many ways through it being embedded in the majority of current technologies. Because of the obvious parallel between climate mitigation and feedback control, it appears logical that some of the numerous tools developed to design and evaluate feedback control systems could be brought to bear on this important area of application. In this paper we start to explore some of these possibilities paying particular attention to the issue of anticipatory and reflexive decision making in mitigation.

Currently, the design and analysis of climate mitigation strategies appears to fall into one of two categories; being either anticipatory or reflexive. Anticipatory methods emphasise the predictability of the climate system and hence use models of that system to project future emissions scenarios required to deliver certain desired outcome(s). Notable methods in this category would include model inversion (e.g Wigley 1991) and model optimisation (e.g. Nordhaus 1991). Reflexive strategies on the other hand emphasise the uncertainty associated with the climate system and hence the role played by online observations when applying sequential corrections to mitigation strategies in order to compensate for the inability to predict the behaviour of the climate system accurately (e.g. Hammitt et al. 1992). Obviously, both paradigms are important, with the anticipatory methods providing valuable lead time for planning and the reflexive methods ensuring ultimate compliance to policy objectives in the face of uncertainty. One potential benefit of analysing climate mitigation from a control systems perspective is that it naturally lends itself to integrating model based anticipatory methods with reflexive online strategies through the explicit consideration of the associated feedback dynamics. This is because feedback control is

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Fig. 1 A schematic block diagram of the feedback relationship between climate responses and their mitigation.