Feedbacks, Timescales, and Seeing Red

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Earth systems dynamics, response times, red noise

Abstract

Feedback analysis is a powerful tool for studying the Earth system. It provides a formal framework for evaluating the relative importance of different interactions in a dynamical system. As such, its application is essential for a predictive or even a mechanistic understanding of the complex interplay of processes on the Earth. This paper reviews the basic principles of feedback analysis and tries to highlight the importance of the technique for the interpretation of physical systems. The need for clear and consistent definitions when comparing different interactions is emphasized. It is also demonstrated that feedback analyses can shed light on how uncertainty in physical processes translates into uncertainty in system response, and that the strength of the feedbacks has a very tight connection to the dynamical response time of the system.

INTRODUCTION

The language of feedbacks is ubiquitous in contemporary Earth sciences. The very notions of Earth systems science and Earth system models embody at their core the concepts and principles of systems dynamics, for which feedback analysis is one of the theoretical cornerstones. The identification and evaluation of positive and negative feedback mechanisms in the Earth system have come to be seen as major research goals.

In tackling the challenge of understanding an Earth system in which everything influences everything else, feedback analysis provides a formal framework for the quantification of coupled interactions. Such systematic characterization is essential if the knotted skein of interdependent processes is to be teased apart and understood. Our confidence in the predictions we make of future states of the system rests on our confidence that the interactions between the constituent elements have been properly defined and their uncertainties characterized. Feedback analysis not only provides information about the magnitude of the system's response to a perturbation, it also supplies a rich picture of the system dynamics. For example, the relative importance of different feedbacks identifies the pathways by which a system adjusts when perturbed. Yet despite its central importance to the interpretation of system dynamics, formal feedback analysis is almost absent in Earth sciences and quite rare even in climate dynamics, where its use is most prevalent.

The history of the recognition of feedbacks is perhaps best described as an emerging awareness. Adam Smith, for instance, had a clear understanding of the feedbacks inherent in the operation of the invisible hand—the set of natural and mutual interactions that govern commerce (Smith 1776). In practical applications, the use of feedback principles to regulate mechanical devices goes back much further. Centrifugal governors, which act to automatically maintain the distance between the bed and runner stones, have been employed in wind- and water mills since the seventeenth century (e.g., Maxwell 1867), and float valves were used by the Greeks and Romans in water clocks. However, the abstract idea of a feedback was first conceived of and formalized by Harold S. Black in 1927. Black was searching for a way to isolate and cancel distortion in telephone relay systems. He describes a sudden flash of inspiration while on his commute into Manhattan on the Lackawanna Ferry. The original copy of the page of the *New York Times* on which he scribbled down the details of his brain wave a few days later still has pride of place at the Bell Labs museum, where it is regarded with great reverence (**Figure 1**). Some of the concepts and consequences of feedbacks are counterintuitive, so much so that it took Black more than nine years to get his patent granted—the U.K. patent office would not countenance it until a fully working model was delivered to them. Only after being convinced that seventy negative-feedback amplifiers were already in operational use were they finally persuaded to issue a patent. Black (1977) writes that "[o]ur patent application was treated in the same manner one would a perpetual motion machine." Since the initial skepticism, the principles of feedback analysis have become widely disseminated in the fields of electrical engineering and control systems. For the latter, in fact, they are the foundational theory.

The notion that internal, mutually interacting processes in nature may act to amplify or damp the response to a forcing goes back at least as far as Croll (1864), who invoked the interaction between temperature, reflectivity, and ice cover in his theory of the ice ages. Arrhenius (1896), in his original estimate of the temperature response to a doubling of carbon dioxide, takes careful and quantitative account of the water vapor feedback that amplifies the response to the radiative forcing. The explicit mention of feedbacks seems to enter the Earth sciences via the climate literature starting in the mid 1960s (e.g., Manabe & Wetherald 1967, Schneider 1972, Cess 1975), and in the popular imagination through the concept of Gaia (Lovelock & Margulis 1974). At first, it appears mainly as a conceptual description of physical processes relating to climate sensitivity.

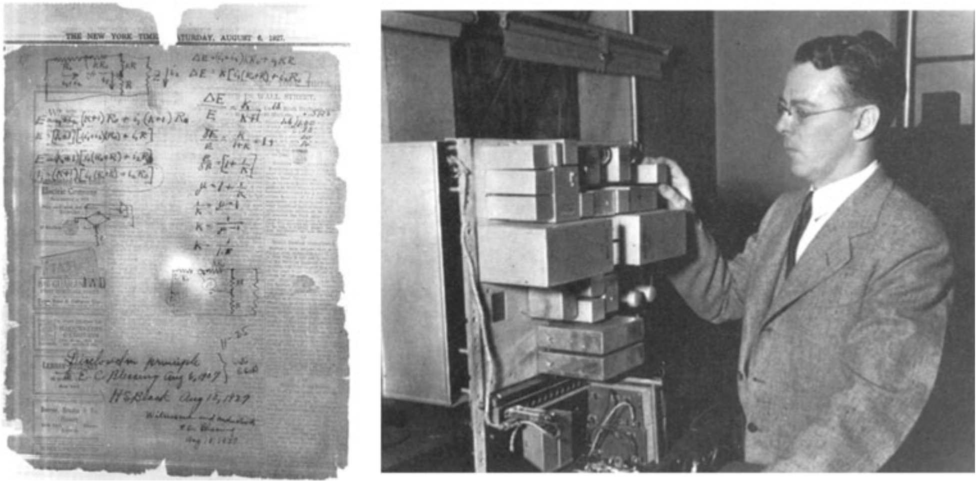

Figure 1

Harold S. Black (1898–1983), inventor of the concept of a negative feedback, and the page of the August 6, 1927 copy of the *New York Times* on which he scribbled a basic outline of his ideas while commuting into Manhattan on the Lackawanna Ferry. Reproduced with permission from Kline (1993) and from the AT&T Archives.

Hansen et al. (1984) and Schlesinger (1985) contributed groundbreaking papers, making quantitative comparisons of different feedbacks in a climate model (but see footnote 4). Since then, there has been a thin but steady stream of studies quantifying climate system feedbacks (e.g., Manabe and Wetherald 1988, Schlesinger 1988, Cess et al. 1990, Zhang et al. 1994, Colman et al. 1997, Colman 2003, Soden & Held 2006).

This purpose of this article is a pedagogic review of the basic principles of feedback analysis. The reasons for this are twofold. First, despite its central importance in Earth systems dynamics, the quantitative analysis of feedbacks is rarely presented in textbooks or even applied in practice. In its most common application, climate dynamics, the literature is confusing and, in some places, flat out contradictory (compare, for instance, Hansen et al. 1984, NRC 2003, Bony et al. 2006, and Torn & Harte 2006 with Schlesinger 1985, Peixoto & Oort 1992, Lindzen 1994, and Wallace & Hobbs 2006; see also footnote 4). Second, although there is a widespread qualitative understanding of feedbacks, there are some useful lessons and subtleties that come from the quantitative analysis, which are not as widely appreciated as they might be. Such aspects of feedbacks have important consequences for the interpretation of climate time series and geophysical data in general. These properties are drawn out and highlighted in this review.

Feedbacks are discussed here mainly in the context of the climate system, which is used as a vehicle for presenting the framework. The extension to other physical systems is direct (e.g., Roe et al. 2008), and in order to keep this extension as clear as possible, many important details of climate feedbacks are not dwelt on. Several excellent studies that do discuss them are cited herein. There is nothing substantially new in what is presented here—material is drawn together from different sources and combined in an effort to provide a coherent framework. It is hoped that there is value in laying out the framework clearly; in emphasizing the fundamental relationships that exist between feedbacks, system response, uncertainty in physical processes, and the timescale of the system response; and in highlighting a few of the many examples where the principles can be seen operating in practice.