MAXIMUM ENTROPY PRODUCTION AND CLIMATE CHANGE EFFECTS

Alastair D. Jenkins

Bjerknes Centre for Climate Research, Geophysical Institute, Allégaten 70, N-5007 Bergen, Norway.
E-mail: alastair.jenkins@bjerknes.uib.no URL: http://www.gfi.uib.no/~jenkins/

Overview

The global climate system, the ecology of the biosphere, biogeochemical cycling, human society and macroeconomics are all very complex processes. The modelling and prediction of these systems is very resource-intensive and subject to considerable uncertainty, for two main reasons: (1) there are generally insufficent data available to estimate model parameters; (2) the model dynamics are often inherently unstable.

Nevertheless, there are some general principles which may be used to constrain the behaviour of such complex systems. One such principle is based on the ideas of thermodynamics and statistical mechanics. An isolated system in thermodynamic equilibrium will tend to a state of maximum entropy, subject to constraints involving the total energy, chemical composition, etc. This is obviously not the case for the coupled climate-biogeochemical-economic system, which is very much in a non-equilibrium state. However, it has been shown that under certain circumstances, the most probable state such a system may be that of maximum entropy production (MEP), subject, again, to appropriate constraints.

This presentation reviews and discusses the applications of the MEP hypothesis, within a historical perspective which includes the development of human activity in northern polar regions. A pointer is given to the effects of predicted climate change on economic activity in northern areas, its possible consequences, and implications for public policy.

Introduction

Although a system of many molecules of different substances in thermodynamic equilibrium has extremely complex behaviour, it was shown by Gibbs [3] to be amenable to rational mathematical analysis.

The thermodynamic entropy S is defined for an isolated system as a state variable which changes as heat Q is supplied to it by the relation

$$S_B - S_A \geq \int_A^B dQ/T, \tag{1}$$

A and B being the initial and final states of the system. For a reversible change (e.g. the slow supply of heat from a source at the same temperature), the inequality in (1) becomes an equality. Gibbs showed the validity of Boltzmann's fundamental relation

$$S = k \log W, \tag{2}$$

with W being the 'volume' occupied by the system in the multidimensional phase space spanned by the positions and momenta of all the molecules, and k being Boltzmann's constant, is also valid for mixtures of substances.

A system in thermodynamic equilibrium will tend to be in a state of maximum entropy, corresponding to maximum 'phase space occupation' W, subject to constraints on total energy, momentum, composition, etc. Jaynes [4, 5] stated the hypothesis that a *non-equilibrium* system should occupy the maximum 'number of paths' going through the phase space, subject to the necessary dynamical constraints, and suggested that this would tend to maximise the *production* of entropy. This maximum entropy production (MEP) principle was verified by Dewar [2], at least for systems in a dynamically stationary state. The MEP principle has been applied with some success to the climate systems of the Earth [10, 11] and of other planets [8].

Entropy production in economic systems

Although the production of entropy, in its information-theoretic sense of randomness, has been shown to be a driving factor in the effectiveness of markets [9], on the macroeconomic scale of whole societies the maximisation of the production of *thermodynamic* entropy, via the consumption of available energy, raw materials, etc., will play a dominant role [6]. The nature of economic and social development and evolution will thus be determined by the physical and other constraints which are placed on entropy production and energy consumption.

Application to the Arctic

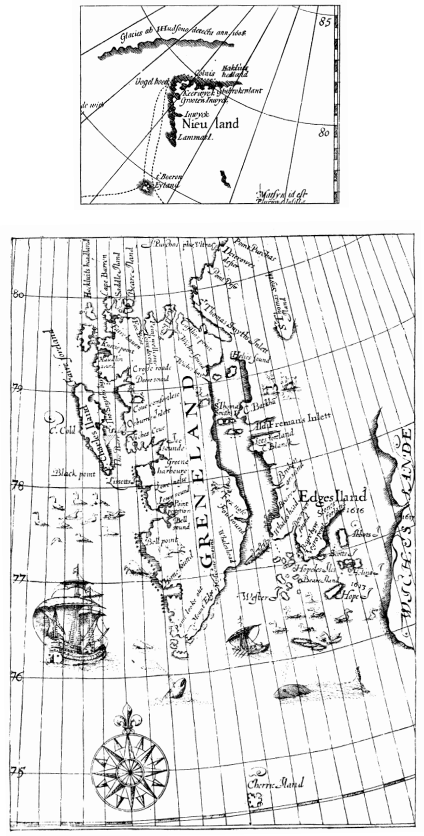

Figure 1. Charts reflecting the economic development of Svalbard [1]. *Top:* Hondius (1611), based on Barents' chart of 1598. *Bottom:* Muscovy Company of London (1625).

We may illustrate the 'entropy production' control of economic systems with reference to Sir Martin Conway's [1] account of the history of Svalbard. Within only a few decades of its discovery in 1596 by William Barents, Spitsbergen became the centre of a thriving whaling and whale processing industry. The main products of this industry were whale oil, used primarily for the production of soap, and whalebone, one of whose uses was the production of decorative objects. These products were generally consumed by the élite and middle classes of Europe, thus adding to the general entropy production of that social group, derived otherwise primarily from solar and freshwater-fuelled agriculture [7].

The industry developed rapidly, with the improvement in shipping, navigation, and processing technology, which led to the removal of constraints for maximising the entropy production. The industry subsequently declined, the land-based processing being abandoned in the 1660s, not least because the killing of whales exceeded their natural increase by reproduction: the maximization of the entropy production by the whaling industry led to the depletion of a natural resource, a phenomenon which is shared with the mineral extraction industry.

The subsequent history of Svalbard shows the same features in the exploitation of other biological resources, including sealing, the hunting of walruses and reindeer, and the trapping of foxes and other land animals for their skins by Russians in the 18th and 19th centuries. This latter activity was made possible by the development of techniques whereby it was made possible to survive in the archipelago during the winter months. In the 20th century, industrial technological capabilities enabled the development of coal mining, an activity which, although not always economically viable, obviously increased entropy production to a great extent. More recently, the development of the 'industries' of tourism and of scientific research allowed the continuation of entropy-producing activities via the consumption of oil fuel in marine and air transportation, in addition to coal consumption for heating. The fishing industry is, of course, another entropy producer, via its fuel consumption and the use of fish and fish products for food and other purposes.

Effect of climate change

As we have seen, economic activities in the Arctic have historically been of an opportunistic nature, exploiting natural and mineral resources to the maximum extent possible, subject to constraints of manpower and technology. More recently, legal constraints have also been put in place to protect the environment and fish stocks, although these legal constraints may also be explained in entropy-production terms, by maximising fish catches and tourism in the medium to long term.

Predicted greenhouse-gas-induced temperature increases in the Arctic may thus be thought of as another 'opportunity': it is clear that in historical times the climate, in particular, the sea-ice conditions, had a substantial influence on the catch of whales, seals, etc. Substantial summer melting of Arctic sea ice will not only enable increased commercial ship traffic in the Russian and Canadian arctic waters, but will also encourage touristic activities such as North Pole cruise traffic. The unpredictable effects of climate change on the marine food chain may have a deleterious effect on some fish stocks, but the opportunistic nature of the fishing industry may lead to the exploitation of new species. Hydrocarbon production in Arctic waters may become less expensive, which will lead to increased exploration and production activities, and also to pressure for the relaxation of legal restrictions on exploitation. A reduction in sea ice will also make ship-based scientific observations easier, and so may at least improve oceanographic and biological data coverage, and, perhaps, the subsequent climate predictability.

REFERENCES

[1] M. Conway. *No Man's Land. A History of Spitsbergen from its Discovery in 1596 to the Beginning of the Scientific Exploration of the Country.* Cambridge University Press, 1906. Facsimile edition, Norbok a.s., 1995.

[2] R. L. Dewar. Information theory explanation of the fluctuation theorem, maximum entropy production and self-organized criticality in non-equilibrium stationary states. *J. Phys. A: Math. Gen.*, 36:631, 2003.

[3] J. W. Gibbs. *Elementary Principles in Statistical Mechanics.* Yale University Press, 1902.

[4] E. T. Jaynes. Information theory and statistical mechanics. *Physical Review*, 106(4):620–630, 1957.

[5] E. T. Jaynes. Where do we stand on maximum entropy? In R. D. Levine and M. Tribus, editors, *The Maximum Entropy Formalism*, page 15. MIT Press, 1979.

[6] A. D. Jenkins. Thermodynamics and economics. Draft manuscript, available for download from `http://www.gfi.uib.no/~jenkins/papers/JenkinsAD_ej20040812.pdf`, 2004.

[7] P. Laslett. *The World We Have Lost.* Methuen, London, 1979.

[8] R. Lorenz et al. *Geophys. Res. Letts*, 28:415, 2001.

[9] E. Maasoumi and J. Racine. Entropy and predictability of stock market returns. *Journal of Econometrics*, 107:291–312, 2002.

[10] G. W. Paltridge. *Quarterly Journal of the Royal Meteorological Society*, 101:475, 1975.

[11] S. Shimokawa and H. Ozawa. *Quarterly Journal of the Royal Meteorological Society*, 128:2115, 2002.

This poster was prepared with Brian Wolven's Poster LATEX macros v2.1.