Non-linearities in the Earth System

by R.A. Pielke Sr, H.J. Schellnhuber, and D. Sahagian

The complex non-linear physical, chemical, and biological interactions among the components of the Earth System are becoming an increasingly important focus in global change research [1]. These interactions between atmosphere, oceans, ice, and land are driven externally by the solar input of heat, and internally by geologic activity and the myriad processes that control the behaviour of each sub-system (Figure 1). Human activity is an integral component of these interactions. At the 3rd IGBP Congress, Banff, Canada, a working group entitled "Development of Earth System models to predict non-linear responses/switches" was convened to review our understanding of this non-linear system. The session built upon an earlier IGBP workshop entitled "Non-linear responses to global environmental change: critical thresholds and feedbacks", held at Duke University, North Carolina, USA, in May 2001. At these meetings, a diverse group of scientists confirmed that each component of the Earth System itself includes complex non-linear feedbacks, in addition to the non-linear interactions between the components. This article draws on the above two meetings to discuss the implications of Earth System complexity for Earth System research, modelling, and prediction.

The complexity of the Earth System's behaviour makes it extremely difficult to accurately forecast the future of the Earth System, and presents a major challenge to the global change research community. New mathematical approaches to assess non-linear behaviour have been explored in recent years to address the problem. Such approaches are taking advantage of advances in the theory of chaotic behaviour and deterministic and stochastic predictability. The goal is to develop techniques for prediction of a system in which many of the components, processes, and thresholds are uncertain or even unknown.

As such, one of the main conclusions of the above-mentioned IGBP meetings was the recognition that the evaluation of key vulnerabilities and sensitivities of the Earth System to human

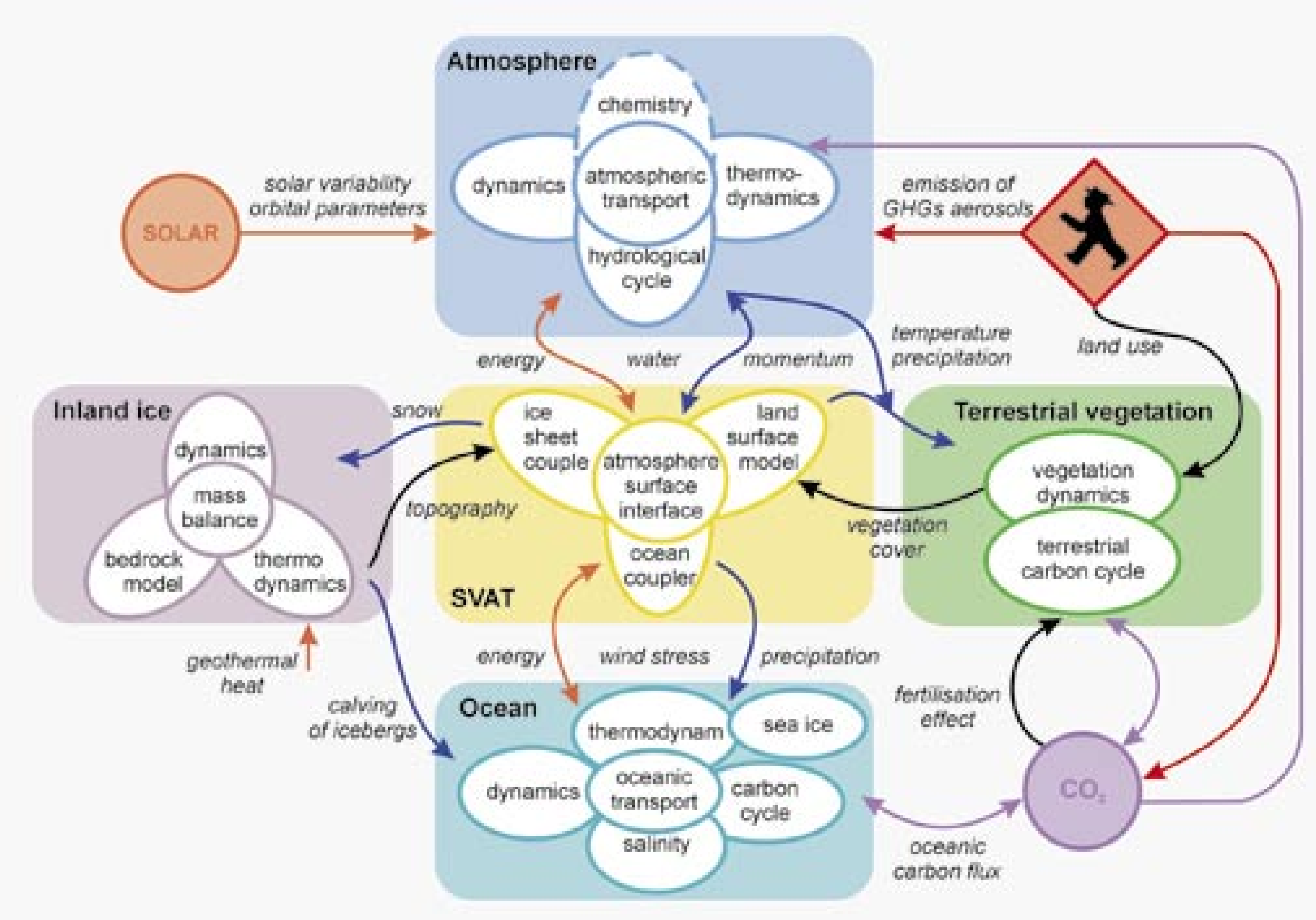

Figure 1: Structure of the CLIMBER-2 model, illustrating the complexity and interactive character of the Earth System [from 1].

and natural perturbation will be of considerable value to policy-makers. Even if skilful forecasts of the behaviour of specific components of the Earth System are not possible, the focus on a vulnerability paradigm permits decision makers to assess the landscape of intolerable domains that exist beyond certain thresholds. These domains can be mapped in “society” versus “natural” phase space, and the various paths by which human civilisation can navigate within the accessible domain, while avoiding intolerable regions, can shed light on the effectiveness of potential global environmental management schemes [2].

The non-linear interactions within the Earth System are on a variety of time and space scales. Abrupt cooling and warming events, for example, are well documented in continental ice cores. Rapid changes in temperature recorded in the cores appear to be associated with changes in fresh water influx into the North Atlantic Ocean, that resulted in circulation changes in the planetary thermohaline ocean circulation [3]. Thus, because the ocean circulation plays a key role in the distribution of the planetary heat budget, fresh water fluxes in the North Atlantic trigger changes in the global climate system. Evidence for very rapid desertification of the Sahara in the mid-Holocene has been found in the geologic record and has been realistically simulated in models of intermediate complexity [4]. The sudden desertification of the Sahara has been attributed to an atmosphere-ocean-vegetation feedback in which the vegetation served to maintain the hydrologic system in the face of decreasing insolation until a critical threshold was passed, after which the vegetation – and the associated hydrology – collapsed suddenly [5]. This latter example demonstrates that vegetation dynamics play an important role in non-linear aspects of the climate system, and must be considered along with atmospheric and ocean processes.

On shorter time scales, irregular variations of the North Atlantic Oscillation, the El Niño Southern Oscillation, and the

Pacific Decadal Oscillation are well documented [6,7,8]. While the reasons for the temporal changes in these climate features are not fully understood, the close coupling between the ocean and the atmosphere has clearly been demonstrated by observations and modelling. Such temporal variations in the Earth System may partly explain the large changes observed in some regional hydrologic and ecological systems during the 20th century. For example, an abrupt change in the annual outflows from African equatorial lakes occurred in 1961, followed by a slow downward trend (Figure 2).

On all time scales, the various non-linear interactions are characterised by drivers and responses that are not proportional. Changes in state are often episodic and abrupt, and multiple equilibria commonly exist. One consequence of such a non-linear system is that forecasts based on current modelling tools should be viewed sceptically. For example, since none of the general circulation models (GCMs) used to project climate change over the next hundred years include all of the important forcings and feedbacks, they should be considered as sensitivity studies rather than forecasts [10]. In Earth System science, climate is not the long term average of weather statistics, but involves the non-linear interactions between the atmosphere, oceans, continental ice, and land surface processes, including vegetation, on all time scales.

Examples of drivers and feedbacks that are typically not accounted for sufficiently in models include land-use change [11], the indirect effect of aerosols [12,13], stratospheric-tropospheric exchanges [14], and vegetation dynamics [15,16]. The ability of clouds to produce precipitation is critically dependent on the available concentrations of cloud condensation nuclei [12,17]. In polluted air masses, clouds rain less and last longer, thus significantly influencing the hydrologic cycle and the radiative forcing of the climate system. Tropical deforestation, and the resultant effect on thunderstorm patterning, alters long-term weather patterns thousands of kilometres from the landscape disturbance [18,19]. Without including non-linear effects such as these, GCM projections of the response of the climate system to increased greenhouse gases are incomplete, and should only be communicated to policymakers with that critical caveat.

As more complete Earth System models are developed – at various levels of complexity [e.g. 4] – one goal is to develop system understanding to the point that the vulnerability of various regions to natural and anthropogenic perturbations can be quantified. Humans are an integral part of this system, hence the interaction of abrupt and extreme events with society is a growing focus of Earth System science [20]. However, unlike other parts of the Earth System, humans can make decisions based on information beyond immediate environmental sensory perception. If Earth System models become more robust, such that their predictions of the environmental impacts of anthropogenic perturbations are considered reliable by the public and policy sector, model results may lead to changes in human behaviour. By doing so, the models themselves alter the system about which they make predictions, although the extent of the alteration of human behaviour on the basis of model results is in itself very difficult to predict. This non-linear feedback loop – that involves the models themselves – can be considered a type of environmental "Heisenberg uncertainty" in which the observer affects that which is observed.

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Research to-date has revealed the need to establish the limits to predictability within the Earth System. It has been shown that climate prediction needs to be treated as an initial value problem with chaotic behaviour. This perspective acknowledges that beyond some time period, our ability to provide reliable quantitative and detailed projections of climate must deteriorate to a level that no longer provides useful information to policymakers. Even in the absence of the ability to provide skilful forecasts, there is, however, a critical societal need to identify parts of the Earth System that are particularly vulnerable to environmental variability. As such, the assessment of certain critical components – in the context of the overall non-linear system, may be useful. For example, one critical issue is water resource development, because it is influenced by environmental variability and change, and because it alters the climate system through irrigation, impoundment, draining of wetlands, and deforestation. Such "hot spots" of Earth System vulnerability need to be identified and monitored so that their non-linear interactions with the rest of the Earth System can be understood in support of policy, strategic land use practices, and general water resource planning [21,22].

The issue of uncertainty also needs to be addressed. There are three types of uncertainty to consider: (i) removable cognitive uncertainty – that can be reduced by targeted scientific research; (ii) irremediable cognitive uncertainty – that cannot be reduced even though individual sub-components follow predictable physical laws; this is typical of many heterogeneous non-linear systems; and (iii) voluntative uncertainty – that is fundamentally insoluble because of the "free will" of large numbers of actors [23]. Plotting any path *a priori* through a realm that includes any or all of these uncertainties is impossible, unless one relaxes control so that the path can be refined and corrected while underway. There are numerous small-scale examples that reflect the "fuzzy control" involved in decision-making under uncertainty. Consider the person walking across a crowded plaza or shopping mall, with a destination in sight, but with no clear path to follow. Setting out the correct general direction, the walker must constantly readjust both speed and direction in order to avoid collisions that would produce unknowable, but generally undesirable consequences. In a similar fashion, general strategies involving management of the Earth System can be adopted initially, with the provision that they be readjusted through time in response to numerous factors, including the documentation of cost and benefit, which are unknown *a priori*. This "soft" decision-making involves the existence of leeway, at least a moderate level of responsiveness, and an overall, or panoramic view of the situation so that decisions can be made in the correct "direction" [24]. This bears strongly on national and international policy-making and the "precautionary principle", yet is poorly understood by policy-makers, the public, and even a large portion of the scientific community.

It is also necessary to train future scientists in this new interdisciplinary non-linear Earth System science. These scientists, while retaining disciplinary expertise, need to become fluent in physical, chemical, and biological sciences, as well as in the science-policy interface. The questions that society needs answered must be identified, so that these scientists can undertake appropriate investigations of the non-linear dynamics of the Earth System [25].

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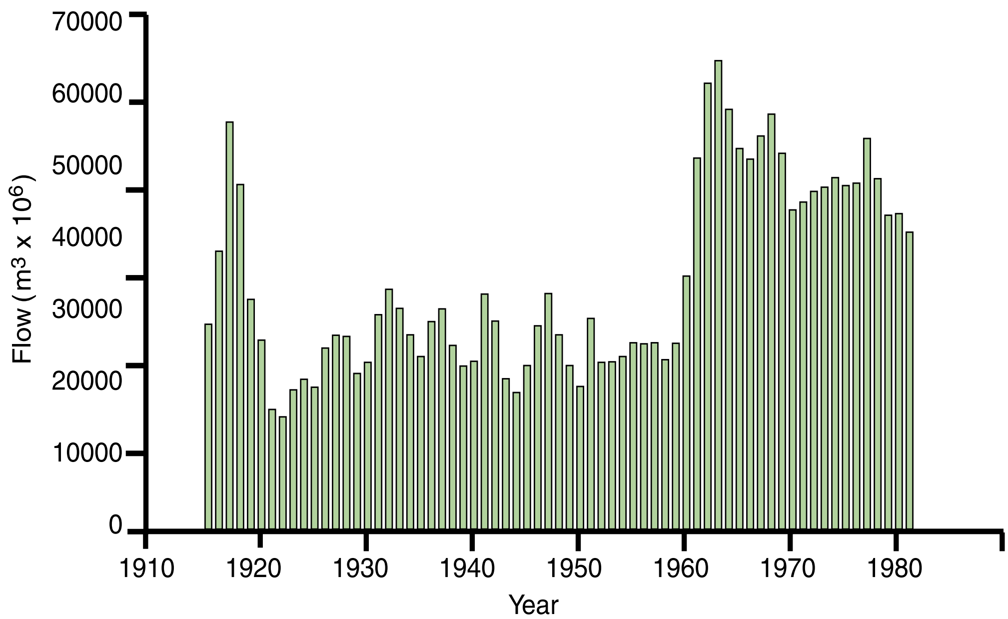

Figure 2: Time series of annual outflows from the African equatorial lakes measured at the Mongala station for the period 1915-1983 showing an abrupt shift around 1961 and a subsequent downward trend [after 9].

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