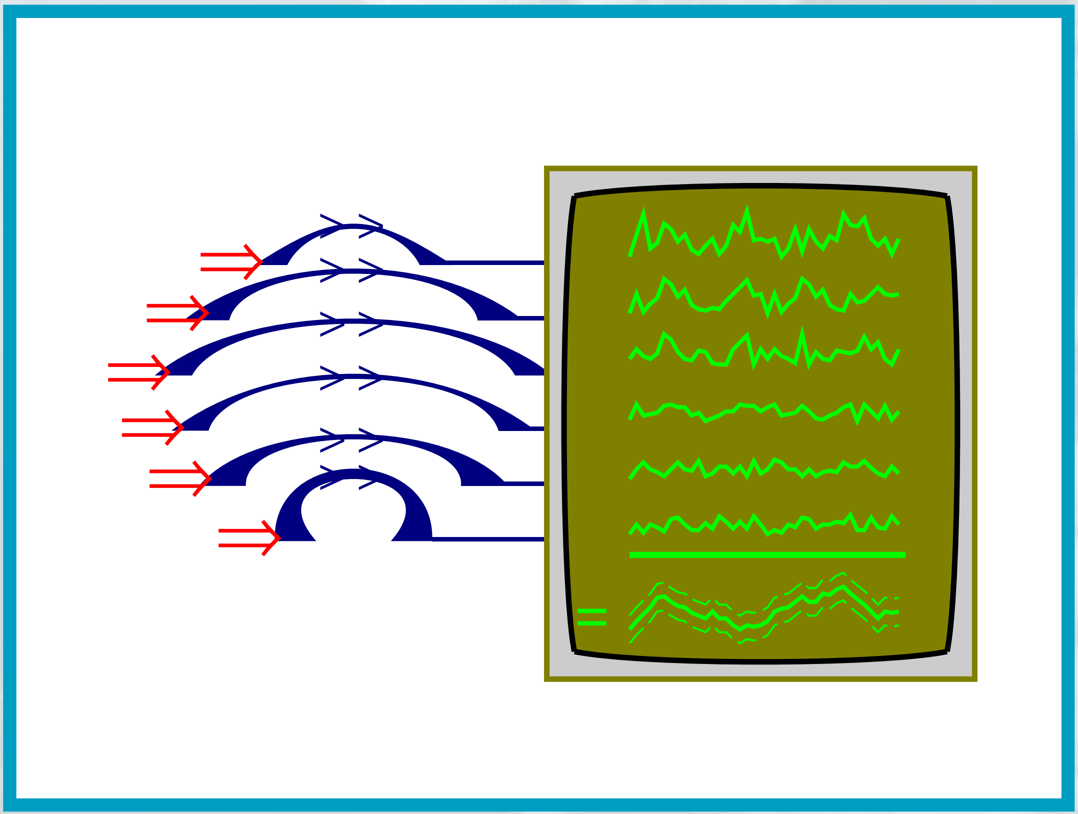
Inverse Problems in Earth System Science: A Complex Systems Perspective

I.G. Enting



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Abstract

The coupled atmosphere-hydrosphere-biosphere-lithosphere system of the Earth represents a challenge to achieving sufficient understanding to be able to address the problems of global change. The Earth System exhibits many of the characteristic features of complex systems: interactions across multiple scales, contingency, nonlinearity and emergent self-organisation. This report proposes that the experience in analysis of the Earth System and its components, in particular data assimilation for weather forecasting, can provide useful examples for the analysis of more general complex systems. In order to demonstrate this assertion, a number of components of the Earth System are considered. In each case, complex behaviour is identified and a number of associated inverse problems are reviewed. In systems characterised by high levels of contingency, inversion techniques, using observations as boundary conditions can provide an alternative to reductionist approaches based on controlled experiments.

1 Introduction

In 2001 the Australian Academy of Science, in a report on research priorities addressed to the incoming Australian government, identified *Complex Earth System Science* as a priority research area (AAS, 2001).

The field of 'Complex Earth System Science' can be regarded as combining elements of two areas of science:

Earth System Science This is the science of the combined atmosphere-hydrosphere-biosphere-lithosphere as an interacting system. One component of Earth System Science is the development of Earth System models, extending the comprehensiveness of existing climate models (see Section 3). However, Earth System Science needs to be much more comprehensive and include interpretive studies of the Earth as a system. An important component of such studies will be the use of remotely-sensed data (NASA, 1986).

Complex system science This is a less well-defined area of study, even to the extent of questioning whether there is such a thing as a theory of complexity (Kadanoff, 2001; as quoted in Section 2 below). Many of the concepts that have been used in discussing complexity have their origin in statistical physics. These are reviewed briefly in the appendix. To some extent, it may seem preferable to talk about 'complex states' rather than 'complex systems' (Cohen and Stewart, 1994). A number of definitions of complexity (Ebeling et al., 2002; and references therein) have been based on the statistics of the putative complex states.

Some the characteristics of systems exhibiting complex behaviour (quoting the summary by the CSIRO Science Investment Focus Group) are:

i They comprise many elements or subsystems connected together in irregular ways;

ii the systems span a large range of dimensions or scales;

iii the connections between the elements of the system are non-linear;

iv the interaction between simpler elements allows self-organisation, that is the emergence of complex structure in space and/or time that is not determined by information or controls imposed externally.

Elaborating on these points: (i) the irregular connections may not be an essential aspect if there are other sources of randomness (see note in Appendix); (ii) the large range of scales often appears as fractal (Mandelbrot, 1977) behaviour with variability exhibiting a power-law dependence on scale rather than exhibiting characteristic length-scales; (iii) non-linearity seems to be essential — in linear systems the composite behaviour can be calculated using the average behaviour of the components; (iv) the 'emergent behaviour' has been taken to mean a variety of different things, most notably the fractal characteristics noted above and the abrupt changes (often with hysteresis) noted below.

The review of complexity and climate by Rind (1999) notes that the climate system exhibits many of these types of complex behaviour but raises the question: *Of what advantage is it to know this?* A partial answer may be that studies of complex systems may at least teach us what sort of questions can be sensibly asked regarding global change. In other words studies of global change need to become part of the general question of: *How do we analyse complex systems?* However, there is a converse to Rind's question: *How can studies of Earth System Science contribute to the more general understanding of complex systems?* One such case has been the ideas of chaos arising from the work of Lorenz (1964; 1993) as one of a number of independent discoveries of this phenomenon (Lorenz, 1993). The premise of the present report is that the practice of data assimilation and similar inverse problems is one in which the experience in the Earth Sciences has much to offer the more general study of complex systems.

Complex system science is sometimes described in terms of being an alternative to a reductionist approach (e.g. Gallagher and Appenzeller (1999)). The manner in which Earth Science problems create difficulties for reductionist approaches is discussed in the following section. For the present, we note that a key component of reductionist approaches is the use of controlled experiment. This is rarely directly applicable in Earth System Science. It becomes necessary to infer the system characteristics indirectly from observations of responses to changes — generally natural changes. The mathematics of producing such interpretation of indirect data to

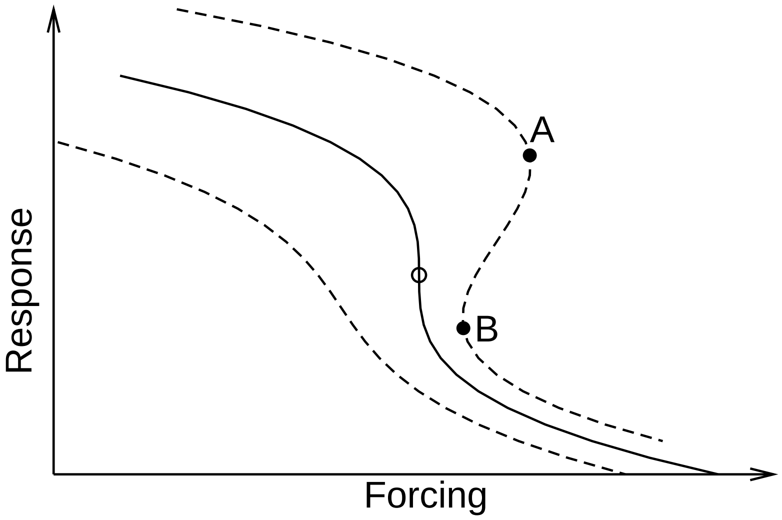

Figure 1: Schematic representation of a non-linear forcing-to-response relation for three successive values of a control parameter. The circle is a singular point (a critical point in thermodynamic applications). Point A represents that limit at which (or before which) increasing forcing must give a discontinuous response. Point B is the corresponding limit of continuous response to decreasing forcing.

infer causes is often termed inverse problems and the calculations are termed inversions. Enting (2000; 2002) defines inverse problems as those in which the direction of the calculation (one of inference) is the opposite to the direction of physical causality. Since many real-world processes are dissipative, losing detailed information about their causes as they evolve, calculations in the opposite direction need to amplify small details. This process inevitably leads to amplification of errors, a characteristic termed 'ill-conditioning'. Indeed a more common practice is to regard ill-conditioning (rather than the relation to the direction of causality) as the defining characteristic of inverse problems. Thus the definition used by Enting (2000; 2002) is non-standard, but has the advantage that the term 'ill-conditioned inverse problem' is not a tautology.

One commonly noted characteristic of complex systems is the emergence of abrupt changes, often with hysteresis. Figure 1 gives a schematic illustration of how this can arise in a non-linear forcing-to-response relation. Three different cases (notionally associated with three different values of a control parameter) are shown. In the first (i.e. leftmost) case, smooth changes in the forcing lead to smooth (albeit non-uniform) changes in the response. The central case has a singular point at the circle. Further change in the control parameter leads to the right-most case, which exhibits hysteresis and/or instability. Increasing the forcing from the left ultimately leads to point A at which point the only possible response corresponds to an abrupt jump to the upper branch of the curve (unless such a jump has already occurred before reaching A). Conversely, coming from the right, an abrupt jump must occur at or before point B.

The discussion of this type of singularity, and an analysis of what other types of singularity are topologically possible, has become known as ‘catastrophe theory’ for which Arnold (1986) noted *“In the early seventies catastrophe theory rapidly became a fashionable and widely publicized theory which by its all-embracing pretensions called to mind the pseudo-scientific theories of the past century.”* In particular Arnold cites Thom as *“but it [catastrophe theory] favorizes a dialectical, Heraclitian view of the universe, of a world in which there is a continual battle between ‘logoi’, between archetypes.”* Arnold’s book reviews the mathematical content of catastrophe theory in terms of analysis of singularities.

This issue of abrupt jumps is of critical importance in Earth System Science where it appears as the question of possible ‘surprises’. Three phenomena that may exemplify such surprises are:

- the ozone hole (Farman et al., 1985);
- potential collapse of the thermohaline circulation (Broecker, 1987) in response to the anthropogenic greenhouse effect;
- potential ecosystem collapse (Cox et al., 2000), also in response to the anthropogenic greenhouse effect and/or other environmental stress;

The remainder of this report is as follows. Section 2 summarises pertinent aspects of complex system science (starting with the question of whether such a thing exists). Section 3 similarly summarises Earth System Science. The subsequent sections, 4, 5, 6 and 7 review particular groups of inverse problems in Earth System Science. Section 8 gives an overview of how Earth System Science might progress beyond a reductionist approach.

2 Complex systems

In the background of this report is the key question: Can one legitimately claim the existence of a field of *Complex System Science*. Sets of review articles, suggesting that there is a new emerging science, have been published by *Science* and *Nature* with overviews by Gallagher and Appenzeller (1999) and Ziemelis (2001) respectively.

Bak (1996; pp. 9–11) takes the view that there can be a theory of complexity. He identifies some of its characteristics as:

- at most it can (and should) explain why there is variability — it will be unable to explain particular variations;
- it must be abstract;
- it must be statistical.

Bak argues that much of physical theory (i.e. statistical mechanics, quantum mechanics and chaotic dynamics) already has such characteristics. Bak proposes the sandpile model (Bak et al., 1987, 1988), which exhibits self-organised criticality as a paradigm for the behaviour of a multitude of complex systems. In a non-technical review, Buchanan (2000; p16) goes further and states that *the ubiquity of the critical state may well be considered the first really solid discovery of complexity theory*

Expressing a somewhat different view, Kadanoff (2001) notes that: *At one time, many people believed that the study of complexity could give rise to a new science. In this science, as in others, there would be general laws with specific situations being understandable as the inevitable working out of these laws of nature. Up to now we have not found any such laws. Instead, studies of specific complex situations, for example the Rayleigh-Bénard cell, have taught us lessons — homilies — about the behaviour of systems with many independently varying degrees of freedom. These general ideas have broad applicability, but their use requires care and judgement. Our experience with complex systems encourages us to expect richly structured behaviour, with abrupt changes in space and time and some scaling properties. We have found quite a bit of self-organization and have learned to watch out for surprises and big events. So even though there is apparently no science of complexity, there is much science to be learned by studying complex systems.*

The perception of complexity can be highly context-dependent. For example:

- Atmospheric dynamics tend to regard chaos as an inherent characteristic of the atmosphere, and do no longer see ‘chaos’ as a new paradigm. Rind (1999) (citing Lorenz in an unjustified identification of chaos and complexity) suggests that “*the very concept of complexity originally arose in concert with atmospheric processes.*”
- In contrast, a number of authors regard fully-developed chaos as too simple to count as complexity and identify complexity as a special state ‘on the edge of chaos’.
- Many physicists would see low-order catastrophes as (a) a long-known concept, and (b) inadequate as descriptions of reality. In particular the curves in Figure 1 can be regarded as three successive isotherms for the van der Waals’ equation for the liquid-gas phase diagram, derived in 1873 (van der Waals, 1873). The forcing is the pressure (increasing to the left) and the response is the volume (increasing upwards). The solid curve is the critical isotherm and the circle indicates the liquid-gas critical point. However, van der Waals’ equation is a poor description of actual liquid-gas critical points (see appendix).
- Fractal behaviour (power-law statistics) has sometimes been taken as a characteristic of complex systems. The concept of fractals (self-similar distributions) was defined by Mandelbrot (1977) who identified such behaviour in many human and natural phenomena. Power-law behaviour arises in cooperative phase transitions and which can be analysed using the techniques of statistical mechanics (see appendix). Fractal behaviour has also been found in other aspects of condensed-matter physics (Feder and Aharony, 1990). As noted above, Buchanan (2000) attached great significance to the wide-spread occurrence of power-law behaviour. However, given the diversity of critical behaviour, power-law behaviour can have only a limited role as a diagnostic.

- A number of workers have proposed algorithmic or computational definitions of complexity [e.g. (Wolfram, 2002) who emphasised the importance of universal computation]. Such a definition would virtually rule out any general laws of complexity of the type discussed by Kadanoff (2001): if a system is described by generic laws then, under algorithmic definitions, it should not be regarded as complex.

As noted above, complex systems science is frequently promoted as an alternative to a reductionist approach. The latter is based on the view that an understanding of the behaviour of a whole system can be obtained from an understanding of the behaviour and interactions of its parts. Conceptually one understands ecosystems in terms of organisms understood in terms of cells understood in terms of biochemistry understood in terms of chemistry understood in terms of atoms understood in terms of sub-atomic 'particles' (and/or fields). In practice, as emphasised by Cohen and Stewart (1994), to the extent that the reductionist paradigm is ever implemented in practice, what is done is to explain each level in terms of particular, carefully selected, 'features' of the behaviour of the components.

One or both of two limitations can prevent this reductionist vision being achieved:

i the computational task of analysing the behaviour is impractical;

ii it is not possible to perform the controlled experiments that are needed in order to determine the behaviour of the component parts.

Frequently, aspects (i) and (ii) appear as complementary difficulties whose relative importance changes depending on the space and/or time scales on which the component parts are considered. If the components are considered on small scales (e.g. laboratory scales) then controlled experiments are possible, but assembling such descriptions into a global-scale representation is computationally impossible. Conversely, if components are considered on scales one or two orders of magnitude smaller than the Earth as a whole, then it is not possible to perform controlled experiments to determine the behaviour of the components.

A further difficulty with reductionist approaches is that:

iii a reductionist approach can direct thinking into following the causal channels associated with reductionist analysis with the risk of ignoring influences from the broader context.

Point (iii) is largely a matter of how reductionist analyses are used. In many real-world problems, it will be necessary to synthesise the information obtained by reductionist analyses into a 'systems view' of the problem. Section 8 notes examples from McMichael (2001) on the need for multiple perspectives in analysing the occurrence of disease.

Some discussions of complexity note that the behaviour of the complex system is influenced much more by the nature of the connections between components than by the detailed features of the components themselves. Such considerations are influenced by statistical physics where the phenomenon is known as universality and can be ‘explained’ by the renormalisation group (Fisher, 1974). For more general complex systems, however, there are not established criteria for the validity of universality or of the applicability of the renormalisation group. Establishing such criteria would be an important part of any general theory of complexity by allowing simplifications in the complex calculations noted in point (i). In the absence of such developments, this report proposes that inversion techniques may provide a viable alternative to the controlled experiments noted in point (ii) above.

3 Earth systems science

This report regards Earth System Science as comprising a mixture of interpretive studies and applications to global change. The perspective is that of anthropogenic change and so the focus is on the faster-acting components of the Earth System — the atmosphere, hydrosphere and biosphere. The outcome of successful Earth System Science would be the understanding to enable the development of strategies for sustainable management of the human impact on the earth.

The progress of climate modelling has been summarised in the IPCC Third Assessment Report (Albritton et al., 2001; Box 3, p 48) as:

Mid 1970s modelling only atmosphere (initially at low resolution but with resolution increasing over time);

Mid 1980s add land-surface;

Early 1990s add clouds, ocean and sea-ice;

Late 1990s add sulfate aerosol;

Present day (i.e. 2000) add carbon cycle and non-sulfate aerosol;

Early 2000s? add atmospheric chemistry.

This represents a progressive development towards models of the whole Earth System. The IPCC description notes that many of the components that are (or are expected to be) progressively added derive from ‘off-line’ models developed previously. Such models are used either for interpretive studies or for projections of specific components of global change, taking their boundary conditions from results of other models.

The process, reflecting a reductionist perspective, of treating global change as a number of separate components is represented schematically in Figure 2. This view forms the basis for defining mitigation activities (e.g. the Kyoto Protocol) both in the general framework and through specifics such as the definition of Global Warming Potentials used to define equivalent emissions (Enting and Law, 2002).

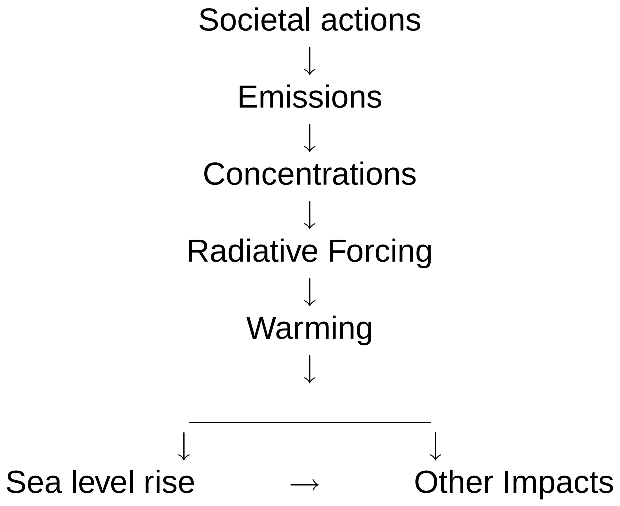

Figure 2: Causal chain from emissions to concentrations to climate change and impacts.

As indicated above, interpretive models of particular components of the Earth System have been developed separately. In synthesising such modelling activities to give an ‘earth-system’ perspective, it is expected that remotely-sensed data will play an essential role in achieving the requisite global data coverage (NASA, 1986). The present report proposes that an important way of using these and other data will be to provide observed boundary conditions for component models. This enables components to be used in inversion studies as a substitute for controlled experiments to analyse their behaviour.

To give a perspective on the Earth System as a complex system, a useful starting point is to consider analyses that see it as a simple system. Two examples are:

- the causal chain illustrated in Figure 2;
- the view of the carbon cycle presented by Sundquist (1985) as a hierarchy of processes at successively longer time scales. At each scale, only a small number of processes are relevant. Processes with longer time scales appear as static boundary conditions; processes with faster time scales can be treated as being in equilibrium — components linked by fast-time-scale processes can be treated as a single component.

A discussion of the need to go beyond such simple analyses and adopt a systems approach is the carbon cycle analysis by Falkowski et al. (2000). They note in particular the range of alternative explanations for the glacial-interglacial differences in atmospheric CO_2 concentrations.

The Falkowski et al. (2000) analysis makes clear the need for a systems approach to the carbon cycle. There are, however, a number of characteristics of the Earth System that indicate that a specifically *complex systems* approach is needed. These include:

- the chaotic dynamics of the circulation of both atmosphere and ocean;
- some studies with coupled atmosphere ocean models found an extreme coupling across scales in that the presence or absence of synoptic-scale variation in the air-sea interaction led to the corresponding presence or absence of a multi-century periodicity in ocean circulation (Weisse et al., 1999);
- the timing of ice ages reflects a complicated relation to orbital forcing;
- the adaptive capability of the terrestrial biosphere needs to be recognised as providing modes of behaviour that go beyond the linearised view of Figure 2 and which operate on multiple scales.

The reductionist view and the linear analysis embodied in Figure 2 is not 'wrong' so much as limited in validity. It will only apply for relatively small changes, beyond which feedbacks can become important and may lead to abrupt transitions to new states. In the words of Broecker (1987) *[we are playing] Russian roulette with climate, hoping the future holds no unpleasant surprises. No one knows what lies in the active chamber of the gun ....*

The basic linear equations describing feedback can be written as

$$c = kf \tag{1}$$

where c is a response, f is the forcing and k is the sensitivity to the forcing. In a feedback case, the forcing is a combination of an 'external' component, f_0, and a feedback component, αc, giving

$$c = k(f_0 + \alpha c) \tag{2}$$

whence

$$c = \frac{k}{1 - k\alpha} f_0 \tag{3}$$

This diverges at $k\alpha = 1$. Real-world systems will, of course, not be literally divergent and will rarely have a change of sign in the response. What the divergence in (3) is telling us is that the linearity assumption will break down at some point with $\alpha < 1/k$. In other words, one has to consider a picture like Figure 1 or something more complicated. Of course, it may well be the case that linearity breaks down for $\alpha \ll 1/k$ — equation (3) merely provides an upper bound. Similarly, Figure 1 describes the simplest manner in which 'runaway feedback' can exhibit itself in real-world systems. The statistical physics analogies (see appendix) imply that more complicated behaviour is more likely.

4 Weather and climate

4.1 Meteorological data assimilation

Weather forecasting is a task undertaken daily (and usually several times a day) by weather services around the world. The primary tool is an atmospheric general circulation model whose time-evolution provides the forecast. The chaotic nature of atmospheric models means that the model results progressively diverge from the behaviour of the real atmosphere. The consequences of this are:
(a) forecasts are limited to times of order 1 week;
(b) the model must be continually matched to observations at the start of each forecast calculation.

This matching process is termed *data assimilation*. An extensive description is given in the book by Daley (1991).

Enting (2002; Section 7.3) has reviewed meteorological data assimilation in comparison to other inversion problems, especially the trace gas inversion described in Section 5.1 below. In particular, he cites Lorenc (1986) as identifying the special features of data assimilation as being:

- a large pre-defined parameter basis, i.e. the variables of the forecast model;
- a set of observations that were far too few to determine these basis components;
- a large amount of prior information from ongoing operation of the forecasting system.

Enting also noted the additional issue that the observed quantities are generally not the dynamical variables used in the models.

Increasingly, assimilation schemes for weather forecasting also need to incorporate information about the land surface, including vegetation, soil-moisture and snow-cover. This is needed so that the forecast model can predict the evolution of surface properties (and their consequent influence on the atmosphere). This imposes an extra degree of difficulty because the time-scales involved in surface processes are longer than those of the atmosphere — a difficulty known as the ‘spin-up problem’ (Daley, 1991).

4.2 Detection and attribution of climate change

The predictions of global warming as a consequence of emissions of radiatively active gases such as CO_2, CH_4 and N_2O raises the question of whether such warming can already be seen to have occurred. Two specific questions are:

- *To what extent is the temperature change over the twentieth century abnormal?*
- *To what extent can abnormal changes during the twentieth century be attributed to anthropogenic emissions?*

These questions, termed ‘detection’ and ‘attribution’ respectively, have been the subject of extensive scientific research, and have been the reviewed in successive IPCC assessments (Wigley and Barnett, 1990; Santer et al., 1996; Mitchell et al., 2001).

Some of the main confounding issues are:

- There is limited knowledge of the scale of natural variability in climate. Relatively sparse global coverage is available for a little over 100 years. Extensions to earlier times rely on isolated records and proxies such as tree-rings.
- There is little direct knowledge, prior to about 1970, of the relative contributions to natural variability from external forcing (solar variations and volcanic aerosol) vs. intrinsic chaotic variation of the atmosphere-ocean-cryosphere system. Long runs with climate models can estimate the latter, but the former relies on proxy data.
- The solar and volcanic forcing during the early part of the twentieth century are not well known, although some proxy data can help constrain these variations.
- The role of aerosols in climate forcing, especially the indirect effects, are not well quantified.

In terms of statistical inference, it is problematic to assign significance levels to estimated changes because of limited understanding of the statistics of the ‘null case’. Issues of detection, attribution and prediction of climate change have been discussed in a complex systems context by Hasselmann (2002).

The practice of detection and attribution of climate change began with ‘curve-fitting’ approaches, matching forcing to long-term temperature records, essentially over the twentieth century. More recently, these have been supplemented by ‘pattern-matching’ studies comparing observed space-time variations to those predicted by climate models. Due to limited data-availability, these comparisons are generally limited to the last few decades.

5 Biogeochemical cycles

5.1 Trace gas inversion

The concentrations of trace gases in the atmosphere reflect the combined influences of sources and sinks and atmospheric transport. Given a knowledge of transport (through an atmospheric transport model) the net source/sink strength can be inferred from the concentrations. The principles and recent practice for such trace gas inversions have been described in a recent book by Enting (2002).

Enting emphasises the technique of ‘Bayesian synthesis inversion’ (Enting et al., 1993, 1995) as providing a basis for both (a) combining multiple types of information and (b) providing estimates that include calculated uncertainties. Bayesian techniques combine new observations with pre-existing information defined as prior distributions. The need to combine multiple streams of information reflects the situation in much of Earth System Science. The calculation of uncertainties is essential, both for scientific credibility and because a knowledge of at least relative uncertainties is required for the optimal combination of information.

The synthesis inversion calculations carried out to date have all been linear estimates. This is appropriate if (i) the relation between sources and concentrations is linear; and (ii) the measurement statistics (and the statistics of the Bayesian prior distributions) are Gaussian. Condition (i) will hold for conserved tracers; condition (ii) is problematic, especially for trace gas records that represent a mixture of ‘baseline’ conditions and ‘pollution events’ (Enting, 2002; Chapter 5). However, even with Gaussian statistics, the experience of synthesis inversion has revealed a number of subtleties. In particular, measurement error is often used as a proxy for the combination of true measurement error and model error. This is justifiable mathematically, but if such an approach is used it has to be realised that for repeat measurements the contributions from true measurement error *may* be independent, but the contributions from model error are likely to have correlations near to 1. Failure to take such correlations into account can give (and has given) severe bias in inversion calculations. Similarly, a neglect of correlation in space or time can lead to unjustifiably small estimates for the uncertainty in aggregated values.

As noted above, the analysis of data records containing both ‘baseline’ and ‘pollution events’ is more complicated than cases analysed to date. Some of the difficulties are due to the complex states arising from advective transport. Even if the advective field has simple time variation (e.g. strictly periodic) and only large-scale variations, tracer transport will be chaotic — the trajectories of neighbouring particles will diverge at some point. Correspondingly, contours of concentration will be stretched into fractal shapes. Two contrasting approaches were presented by Enting (2000) and Prinn (2000) at the Heraklion conference on *Inverse Methods in Global Biogeochemical Cycles.* Prinn emphasised the advective nature while Enting emphasised current practice, which uses a combination of baseline data selection and time averaging to produce records that are effectively smoothed and that make the atmospheric transport appear diffusive. This removes the effects of complexity in the advective transport, at the expense of neglecting much useful information. Techniques to utilise more of the information in non-baseline data are currently being investigated, e.g. (Law et al., 2002).

In a series of recent developments, trace gas inversions have been generalised from calculations that estimate gas fluxes to calculations that estimate properties of the processes responsible for these fluxes. One example is the study by Knorr and Heimann (1995). The theoretical basis is described by Rayner (2001). Enting (2002; Section 12.4) notes a number of inversion calculations that can be regarded as forerunners of this type of process inversion.

5.2 Chemical data assimilation

The techniques noted in the previous section (and described at length by Enting (2002)) are directed primarily at studies of long-lived greenhouse gases. Enting (2002; Section 7.4) briefly noted the emerging area of chemical data assimilation. Generally this involves the incorporation of concentration data, observed from satellite remote sensing, into a chemical transport model.

Compared to inversions of surface concentrations of greenhouse gases, these chemical data assimilations differ through being generally non-linear, having more varied objectives, and involving diverse data. Exploring each of these aspects in turn:

- Chemical reactions involving two reactants introduce non-linearity through the dependence of the rate on the product of the concentrations. An additional non-linearity is introduced by atmospheric transport: transport preserves the mixing ratio (mass of trace gas per unit mass of air) while chemical reaction rates depend on concentrations (mass of trace gas per unit volume of air). Other complications are the existence of catalytic cycles of reactions such as those involved in ozone destruction by nitrogen oxides or by halogenated compounds. This can even lead to ‘run-away’ phenomena such as the ozone hole where, at certain altitudes in spring, there is almost complete loss of ozone.
- The objectives of chemical data assimilation can include source estimation, determination of chemical reaction rates and estimation of atmospheric circulation. Indeed, the earliest observations of ozone distributions were undertaken primarily to diagnose atmospheric transport.
- The various trade-offs involved in different remote sensing techniques lead to different characteristics of the inverse problems. An example of the types of trade-off is the choice between obtaining vertical profiles from reflected radiation vs. cross-sections by solar occultation measurements. The latter can achieve much higher resolution while the former generally has low vertical resolution because vertical information has to be obtained indirectly (e.g. from deconvolution of pressure-broadening effects). The other side of the trade-off is that horizontal resolution of occulation experiments are restricted to two locations per orbit while vertical profiles can be obtained over all (or almost all) of the daylight part of the orbit (or at least the cloud-free parts of the orbit).

Given these complications, it is perhaps not surprising that initial applications of chemical data assimilation have concentrated on gases such as CH_4, which are long-lived, thus controlled by large-scale (in space and time) averages of source/sink processes (Ménard et al., 2000; Ménard and Chang, 2000). Other recent accounts of techniques and applications are cited by Enting (2002; Section 7.4).

5.3 Terrestrial systems

Terrestrial ecosystems and their coupling to the atmosphere-ocean climate system add a new level of complexity. The glacial-interglacial cycles of concentration of CO_2 and CH_4 show a clear relation between climate and gas concentrations. The relative amplitudes of the changes suggest that these are primarily climate changes affecting gas concentrations. There is also an apparent climate signal in CO_2 concentrations over the period of the Little Ice Age. Isotopic data indicate that the Little Ice Age variation is a specifically terrestrial effect (Trudinger et al., 1999; Trudinger, 2000).

A number of connections between climate and terrestrial ecosystems are readily identified. In particular both primary production and respiration tend to increase with temperature, but respiration increases more rapidly, leading (in principle) to a positive CO_2-climate feedback. Feedback process between the climate system and the terrestrial biota are reviewed in the various contributions to the volume edited by Woodwell and MacKenzie (1995) and in chapters of the IPCC Second Assessment (Melillo et al., 1996) and Third Assessment (Stocker et al., 2001).

The basic principles of feedback were illustrated by equations (1), (2) and (3) above. These equations are linear and therefore averaging over feedback factors, α, for individual components would be valid. However, as discussed above, the normal situation is that non-linear effects become important once a system starts to become unstable. Thus positive CO_2-climate feedback is likely to imply a succession of individual ecosystem collapses rather than a single global instability. Consideration of multiple scales becomes essential in analysing this problem. Although Broecker's comments (Broecker, 1987) about surprises were primarily addressing oceanographic changes, large-scale ecosystem instability remains a possibility. A recent integration of climate model with interactive biota suggests a potential for the Amazon rain forest to convert to savannah in response to climate change (Cox et al., 2000). Scheffer et al. (2001) have discussed transitions between different ecosystem states in more general terms, emphasising the concept of *resilience* as a measure of the stability of particular states.

However, even without any coupling to the climate system, biological systems can exhibit complex states. May (1974) produced a simple single-species population model and showed that under some conditions it could exhibit chaotic behaviour.

A new feature of complexity is the adaptive capability of living systems. The term ‘adaptive’ can, of course, refer to many different processes acting on a wide range of scales. Examples from this range are:

- changes in physiological (or behavioural in the case of animals) responses in response to changed environments;

- ecosystem change by species replacement (succession);
- evolution of new species;
- evolution of whole new co-adapted ecosystems.

The extreme (but hypothetical) limit of adaptation by the biota is the Gaia hypothesis (Lovelock and Margulis, 1974; Lovelock, 1979), discussed in Section 7.1, proposing that the biota regulate the physical climate system.

6 Ocean inversions

6.1 Ocean circulation

The classic ‘ocean inverse problem’ is the estimation of the thermohaline circulation of the ocean from measurements of temperature and salinity. These are the quantities which, through their effect on density, drive the circulation. The book by Wunsch (1996) is devoted to this problem. For many years, such calculations were severely data-limited. However, over the 1990s, through the World Ocean Circulation Experiment (WOCE) (Siedler et al., 2001), extensive data sets have been obtained for selected cross-sections of the ocean, including repeat sampling to address issues of change and variability. Satellite altimetry has also provided extensive new data sets for interpreting ocean dynamics.

Scale issues appear in a number of ways, including:

- The eddies in ocean circulation have a much smaller spatial scale than those in the atmosphere. This has meant that until relatively recently, limits on computing power prevented global ocean models from being run with sufficient resolution to resolve the eddies.
- The small water movements associated with the tides generate an ocean mixing process whose inclusion is important for accurate ocean modelling. (This needs to be done through parameterisations, since ocean models lack the resolution required for explicit modelling of tides).
- A series of studies (Weisse et al., 1999; and references therein) have found that the inclusion of synoptic-scale atmospheric variability in air-sea interaction (rather than using averages) affects the long- (up to multi-century-) time-scale features of the circulation in an ocean GCM.
- Deep water formation occurs in limited areas at high northern and southern latitudes. The processes are non-linear due to the water-ice phase transition and the density minimum (as a function of temperature) in the phase diagram of water. Density changes associated

with brine rejection as salt-water freezes provide a further complication and will couple the process to seasonal cycles. Goosse and Fichefet (1999) present a model study that examines the sensitivity to the competing non-linear effects and assesses which processes actually determine whether (or not!) deep water is formed in particular regions.

The issue of feedbacks between the climate and the ocean circulation is the basis of the concerns expressed by Broecker (1987). A number of climate model studies have suggested that global warming will increase the stratification of the oceans, reduce the thermohaline circulation and thus reduce the ability of the oceans to take up heat. From the discussion above, it will be seen that such effects may be very sensitive to details of the process forming deep water. However, the period known as the Younger Dryas (a rapid short-term return to cold conditions early in the present interglacial) is commonly attributed to the disruption of deep water formation by the release of fresh (i.e. low-density) water from melting ice sheets. The stability of the thermohaline circulation has been discussed from a complex systems perspective by Kropp et al. (2002). The overall issue of feedbacks between oceans and climate has been reviewed in successive IPCC assessments (Denman et al., 1996; Stocker et al., 2001).

It is only recently that assimilation of data into time-dependent models of the ocean circulation has become feasible (Stammer et al., 2002; and references therein). This type of capability will be essential for seasonal weather forecasting (i.e. predicting seasonal averages). Coupled atmosphere-ocean modelling is beginning to achieve useful forecasting skill, although some current operational capability still draws on statistical techniques based on indices of ocean state.

6.2 Ocean tracer inversions

Precursors of ocean tracer inversions can be found in the calibration of ocean mixing in carbon cycle models using ^{14}C e.g. (Oeschger et al., 1975; Broecker et al., 1980). A more comprehensive multi-tracer inversion (using carbon, alkalinity, phosphorus, oxygen and ^{14}C) was developed by Bolin et al. (1983). This type of inversion involves simultaneous estimation of physical transport, air-sea exchange, biological transport and particulate formation and redissolution. Bolin et al. noted that, as the resolution increased, the number of unknowns increased faster than the number of data points.

These and similar inversions of measurements of trace constituents in the ocean initially developed with little connection to physical oceanography. However, ^{14}C distributions have been widely used as a check on ocean general circulation models. The significance of using ^{14}C is that its radioactive decay (with half-life of 5730 years) provides an absolute time-scale for the ocean-mixing processes.

Generally, ocean tracer inversions have aimed to estimate a mean circulation, and data have been assumed to reflect such a mean circulation. To the extent that temporal variations in circulation lead to variability in concentrations, such variability needs to be regarded as part of the ‘data noise'. In the absence of repeat sampling, the amplitude of such 'noise' will be poorly known. Initial studies generally used tracers with steady-state distributions. As noted above, natural ^{14}C provided the time-scale. Later studies have used observations of transient tracers: ^{14}C and tritium from nuclear testing, along with the various chlorofluorocarbons (Brewer et al., 1985).

Recently a synthesis inversion technique (c.f. Section 5.1) has been applied to ocean tracer data (Gruber et al., 2001) and combined inversions have been undertaken using both chemical data and the traditional variables (temperature and salinity) from physical oceanography (Ganachaud and Wunsch, 2000).

7 Cross-cutting issues

7.1 Other problems

The examples given in the previous sections illustrate the range of inverse problems that occur in Earth System Science, as well as noting particular aspects relevant to the study of the Earth as a complex system. Other areas of importance include (without any pretence of completeness):

hydrology Hydrological studies are an important part of earth system science. Notably, there is a wide spread in precipitation changes predicted by different climate models. A number of hydrological inverse problems are associated with the surface data assimilation discussed in Section 4.2. Other hydrological inverse problems involve ground-water, nutrients and soil processes.

glaciology The large-scale issue is that of relating the occurrence of glacial-interglacial cycles to the Milankovitch orbital forcing. The problem is to identify the processes that determine the complicated phasing of forcing and response and that amplify the apparently small radiative effects. Hargreaves and Annan (2002) describe the assimilation of paleo-data into a simple climate model to tackle this problem.

Gaia The Gaia hypothesis (Lovelock and Margulis, 1974; Lovelock, 1979) proposes that the physico-chemical Earth System (the geosphere) and the biota act as a coupled system, with the biota acting to stabilise physical and chemical conditions in a way that preserves conditions on earth as favourable for life.

The Gaia hypothesis has been subject to many criticisms. Two important strands of criticism have been:

- The Gaia hypothesis lacks scientific content. In particular the Gaia hypothesis is claimed to be untestable. The most extreme form of this is to ask: *Is the Gaia hypothesis science or religion?*
- A Gaian state is unachievable by evolution through natural selection.

This second criticism has been raised very forcefully by Dawkins (1982): *'The fatal flaw in Lovelock's hypothesis would have instantly occurred to him if he had wondered about* *the level of natural selection process which would be required in order to produce the Earth's supposed adaptations.'* In other words, the planetary biota as a whole is not a unit of selection. Recent work by Lenton (1998) aims to address this criticism, but can at best be regarded as only a first step. However, seen from a complex systems perspective, the wording of Dawkins' criticism may contain the seed of an answer — the assumption of a (single) *level* for natural selection may turn out to be unjustified.

Socio-economic systems The incorporation of socio-economic aspects of global change introduces new feedback loops from each of the stages shown in Figure 2. This necessitates defining new ways of looking at such systems. A simple illustrative example is the current disagreement (Schneider, 2001; Grübler and Nakicenovic, 2001; Pittock et al., 2001) as to whether it is possible and/or desirable to assign probabilities to the 21st century emission scenarios developed by the IPCC. One of the proposed applications of such probabilities is as a starting point for propagating uncertainties through the causal chain shown in Figure 2. This causal chain underlies the efforts of the Framework Convention on Climate Change in avoiding harmful climate change. In the words of Hulme (2000) *the real challenge for climate change science is not to be able to predict future climate; rather it is to give society the options to choose its own future climate.* However, the potential for abrupt changes raises doubts as to whether it will really be possible to choose (on the basis of comparing alternative projections) the future climate.

7.2 Multiple constraints

One of the characteristic features of complex systems was identified as being the interaction of multiple scales. In the 'simplest' type of complex system, these interactions are all of the same type, allowing analyses in terms of these scales, most notably through renormalisation group techniques. In more complicated complex systems different processes dominate at different scales (with cross-linking between scales precluding a hierarchical 'reductionist' analysis). In still more complicated systems different scales require totally different perspectives — the various viewpoints on human disease (McMichael, 2001; see section 8 below) are a powerful illustration of this point.

The contributions from multiple processes and multiple scales imply a need for multiple types of data, requiring us to go beyond the types of estimation applied to many classic inverse problems. The Bayesian approach noted above provides a consistent framework for use of multiple data types. (In contrast, many other regularisation techniques become inapplicable for inverting multiple data streams, through lack of a common metric for applying regularisation). In particular, the Bayesian approach:

- provides an appropriate regularisation of ill-conditioned problems, even if only one type of data is involved;
- handles the use of multiple data sets consistently. Going from a prior distribution, $f_0(.)$ using data c_1 to obtain a posterior distribution f_1 and then using this as a prior distribution

when using data c_2 to obtain posterior $f_2(.)$, gives the same result as starting from prior $f_0(.)$ and using a composite data set $[c_1, c_2]$ to obtain $f_2(.)$.

- corresponds to the way the science actually works, building on existing knowledge.

The need and scope for a multiple constraints approach is discussed by Kruijt et al. (2001) in the context of the CARBOEUROPE cluster of projects. They noted the potential for combining data from ecosystem inventories, flux towers, boundary-layer budgeting and remote sensing. (See also (Enting, 2002; Section 17.4) for a summary and additional references).

An example of the scope for improving the use of multiple data sources was noted by Enting (2002; Section 17.2), in the study of pollution sources. One class of studies estimate sources, s from concentrations, c by inverting the transport relation $c = As$, assuming perfectly-known transport. Another class of methods relate multiple tracers by $c_j = As_j$ assuming nothing about transport A, except that the same transport applies for all tracers. This allows estimates of the form $\hat{s_j} = s_{\rm ref} \times c_j/c_{\rm ref}$ if the (co-located) sources of some reference tracer are known. Neither of the extreme assumptions (perfect knowledge or zero knowledge) concerning atmospheric transport can be regarded as the 'best' representation of our knowledge, implying that a composite estimation technique would produce more precise results.

As noted above, remote sensing from satellites will play an increasing role in providing the data needed in earth system science (NASA, 1986). Remote sensing studies have also played an important role in the development of inversion techniques for more general problems through, for example, the work of Twomey (1977) and Rodgers (1976; 2000).

Generally, the use of remotely sensed data involves a 'double' inverse problem. Typically a deconvolution is required to obtain a physical quantity such as gas concentration and a second inverse problem (of the types discussed throughout this report) is required in order to interpret the estimated concentrations.

7.3 Contingency

Regardless of the semantic question of whether chaotic behaviour is a *sufficient* condition to indicate complexity, many undoubtedly complex systems exhibit chaotic behaviour (or chaotic states). While the state of the atmosphere is a classic example (leading to the 'butterfly effect' metaphor (Lorenz, 1972)), sensitive dependence on initial conditions is found in systems that appear much simpler – e.g. the three-body problem in celestial mechanics (Lorenz, 1993; citing work by Poincaré).

As noted above, many of the concepts that are being used to characterise complex systems have their origins in statistical physics. Particularly influential has been the sandpile model (Bak et al., 1987, 1988). Notionally this is a model of avalanches on a pile of sand that gains grains from a steady source and loses grains as avalanches cross an outer boundary. Compared to models of thermodynamic states, this model has the surprising characteristic that it achieves a critical state (characterised by power-law behaviour of avalanche size) without the adjustment of a control parameter. The phenomenon is termed self-organised criticality. Sizes of particular avalanches have a sensitive dependence on the initial state.

Sensitive dependence on initial conditions is essentially the norm in the 'historical' science, almost by definition. The sandpile model has been used (Bak, 1996; Buchanan, 2000) as a paradigm for contingent phenomena from earthquakes to stock market crashes to world wars.

An 'admission of defeat' in the face of contingency is in the final words from Gould (1989) *'. . . — why do humans exist? A major part of the answer, touching those aspects that science can treat at all, must be because* Pikaia *survived the Burgess decimation. This response does not cite a single law of nature; it embodies no statement about predictable evolutionary pathways, no calculation of probabilities based on general rules of anatomy or ecology. The survival of* Pikaia *was a contingency of "just history". I do not think that any "higher" answer can be given and I cannot imagine that any resolution could be more fascinating.'* In this context, *Pikaia* refers to a minor species in the fauna of the Burgess shale from the early Cambrian. *Pikaia* is the only chordate (the phylum that includes vertebrates) present. Earlier, Gould is quite explicit that this sort of reference to the survival of *Pikaia* is a shorthand meaning the survival of one particular species (the one that was our ancestor) of those (apparently few) chordates existing at that time.

In contrast to the theme of contingency presented by Gould (1989), Conway Morris (1998) suggests that there are constraints (from biology, chemistry and physics) that restrict evolution to a limited range of possibilities. He cites the case of South America where, during the period in which it was separate from other land masses, evolution proceeded in comparable directions to the rest of the world.

Clearly, two important questions for systems dominated by chaos/contingency are:

- How far ahead can we make specific predictions? (How many days ahead can we predict the weather?)
- How well can we determine the range of the space over which chaotic variability will range? (How well can we predict how the climate will respond to changed boundary conditions?).

These questions recur in inversion problems, as exemplified by the different approaches proposed by Prinn (2000) and Enting (2000), the former noting the chaotic nature of atmospheric transport and seeking to use this as part of the data fitting, the latter looking for the long-term averages that do not depend on tracking a specific state. Further work remains to be done on establishing the domains of validity (and optimality) of the two approaches.

The issues in inversion mirror those associated with prediction, defining the question:

- how does the resolution of useful information from the past degrade as one looks further back? — how much past data can be usefully assimilated? — what are the appropriate ‘spin-up’ times for data assimilation in various types of system?

8 New perspectives

The various aspects of Earth System Science reviewed in the previous sections confirm the need to go beyond a reductionist approach, adopting a systems view and more specifically, a complex systems view.

Powerful examples of what a systems approach can mean in practice are given in McMichael’s book *Human Frontiers, Environments and Disease* (McMichael, 2001). This examines various diseases, noting the multiple perspectives involved including:

- the perspective of a doctor seeking to treat an individual patient;
- the public health view, assessing which aspects of society affect the incidence of particular diseases;
- the evolutionary perspective which, depending on the disease, may be (a) the reasons why evolution has failed to select against ‘lifestyle’ diseases (most notably those that typically occur later than child-bearing/rearing); (b) the co-evolution of humans and pathogens; (c) the societal changes that allow ‘new’ pathogens to become established (and evolve) in human populations.

McMichael (2001) has noted the importance of complex systems approach in analysing these issues. The multiple (interacting) perspectives illustrated above are analogous to (and a generalisation of) the multiple interacting scales that are regarded as characteristic of complex systems.

The discussion of terrestrial biotic systems raises the issue of complex adaptive systems. The issue of adaptation becomes far more complicated when the analysis of the Earth System is expanded to include the socio-economic components that both drive aspects of Earth System change and are impacted by Earth System changes.

In referring to socio-economic adaptation, it must be recognised that adaptation refers to changing behaviour in response to the environment. It does not carry any implication of beneficial adaptation. Indeed it is quite possible for socio-economic responses to be mal-adaptive. An important difficulty in achieving beneficial adaptations is the mis-matches between the space and time scales relevant to global change and the space and time scales on which human decision-making occurs.

9 Conclusions

The development of Earth System Science will require an extensive program of observations and interpretive modelling, in order to develop an understanding of how the combined atmosphere-hydrosphere-biosphere-lithosphere system functions. Using this knowledge for sustainable management of the Earth System will require a systems view, well beyond single disciplinary approaches, and will require integration of socio-economic aspects of global change.

A systems approach is generally seen as a replacement for a reductionist approach. As discussed above, this should not be seen as implying that a reductionist approach is false, simply that it may be inapplicable in practice and it may tend to focus attention on the wrong questions. A systems approach seems to be required in systems with multiple components and many cross-connections between these components. The use of inversion techniques is presented in this report as a way of getting back to the spirit of the reductionist approach by using inversion as a substitute for controlled experiment when trying the determine the properties of system components.

For systems that exhibit (or have the potential to exhibit) complex states, an additional level of difficulty arises. The terminology used in this report would imply that non-linearity, even when strong enough to lead to instabilities and hysteresis, is not in itself sufficient to justify classing a system as ‘complex’. Rather, it is having such behaviour depend on multiple scales, more complicated than can be quantified by simple averaging, that constitutes ‘complexity’ in such cases.

The appearance of such complex behaviour introduces a new level of complication in inverse problems in such systems. Treating the inversion problem as an estimation problem, extracting an attenuated signal in the presence of noise (Enting, 2002), the possibility of power-law statistics in the signal and/or noise may imply a requirement for new forms of statistical analysis.

The preceding sections have reviewed a number of the components of the Earth System along with associated inverse problems. The inverse problems differ widely in the types of data available and the degree of complexity in the system behaviour. For these different situations a range of differing inversion techniques have been developed. This report does not attempt to describe or characterise them, referring the reader to specialist accounts (Enting, 2002; Wunsch, 1996; Daley, 1991; Rodgers, 2000). The point is that this diversity provides a range of approaches for possible analysis of other complex systems.

To mis-appropriate a currently popular terminology, the triple-bottom-line of this report is:

- Earth System Science can, in part, recapture aspects of the reductionist approach through the use of inversion approaches as a substitute for controlled experiment;
- inversions in Earth System Science need to use statistical approaches that recognise complex system behaviour, most notably power-law behaviour;
- the experience of inversions in Earth System Science, and in particular the operational use

of data assimilation in weather forecasting, may provide valuable lessons for the study of other complex systems.

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References

AAS (2001). Priorities in research and innovation for the next Australian government. (Australian Academy of Science: Canberra). Available from: *http://www.science.org.au/academy/media/priorities.pdf* .

Albritton, D. L., Meira Filho, L. G., et al. (2001). Technical summary. In Houghton, J. T., Ding, Y., Griggs, D., Noguer, M., van der Linden, P., Dai, X., Maskell, K., and Johnson, C., editors, *Climate Change 2001: The Scientific Basis,* pages 21–83. Published for the IPCC by CUP, Cambridge, UK.

Arnold, V. I. (1986). *Catastrophe Theory*. Springer-Verlag, Berlin, second English edition.

Bak, P. (1996). *How Nature Works: The Science of Self-Organized Criticality*. Springer-Verlag, New York.

Bak, P., Tang, C., and Wiesenfeld, K. (1987). Self-organized criticality: an explanation for 1/f noise. *Phys. Rev. Lett.*, 59:381–384.

Bak, P., Tang, C., and Wiesenfeld, K. (1988). Self-organized criticality. *Phys. Rev. A*, 38:364–374.

Baxter, R. J. (1982). *Exactly Solved Models in Statistical Mechanics*. Academic Press, London.

Binder, K. and Heermann, D. W. (1988). *Monte Carlo Simulation in Statistical Physics*. Springer-Verlag, Berlin.

Bolin, B., Björkström, A., Holmén, K., and Moore, B. (1983). The simultaneous use of tracers for ocean circulation studies. *Tellus*, 35B:206–236.

Brewer, P. G., Sarmiento, J., and Smethie, W. M. (1985). The Transient Tracers in the Ocean (TTO) program: The North Atlantic study, 1981; the tropical Atlantic study, 1983. *J. Geophys. Res.*, 90C:6903–6905.

Broecker, W. S. (1987). Unpleasant surprises in the greenhouse. *Nature*, 328:123–126.

Broecker, W. S., Peng, T. H., and Engh, R. (1980). Modeling the carbon system. *Radiocarbon*, 22:565–598.

Buchanan, M. (2000). *Ubiquity: The Science of History . . . Or Why the World is Simpler than We Think*. Weidenfeld and Nicholson, London.

Cohen, J. and Stewart, I. (1994). *The Collapse of Chaos: Discovering Simplicity in a Complex World*. Penguin, London.

Conway Morris, S. (1998). *The Crucible of Creation: The Burgess Shale and the Rise of Animals*. OUP, Oxford.

Cox, P. M., Betts, R. A., and Jones, C. D. (2000). Acceleration of global warming due to carbon-cycle feedback in a coupled climate model. *Nature*, 408:184–187.

Daley, R. (1991). *Atmospheric Data Analysis*. CUP, Cambridge, UK.

Dawkins, R. (1982). *The Extended Phenotype*. OUP, Oxford.

Denman, K., Hofmann, E., and Marchant, H. (1996). Marine biotic responses to environmental change and feedbacks to climate. In Houghton, J. T., Filho, L. G. M., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K., editors, *Climate Change 1995: the Science of Climate Change*, pages 483–516. Published for the IPCC by CUP, Cambridge, UK.

Ebeling, W., Molgedey, L., Kurths, J., and Schwarz, U. (2002). Entropy, complexity, predictability, and data analysis of time series and letter sequences. In Bunde, A., Kropp, J., and Schellnhuber, H. J., editors, *The Science of Disasters: Climate Disruptions, Heart Attacks, and Market Crashes*, chapter 1, pages 3–25. Springer-Verlag, Berlin.

Egolf, D. A. (2000). Equilibrium regained: From nonequilibrium chaos to statistical mechanics. *Science*, 287:101–104.

Enting, I. G. (1985). A lattice statistics model for the age distribution of bubble trapping in polar ice. *Nature*, 315:654–655.

Enting, I. G. (1993). Statistics of firn closure: a simulation study. *J. Glaciology*, 39:133–142.

Enting, I. G. (2000). Green's function methods of tracer inversion. In Kasibhatla, P., Heimann, M., Rayner, P., Mahowald, N., Prinn, R., and Hartley, D., editors, *Inverse Methods in Global Biogeochemical Cycles*, volume 114 of *Geophysical Monograph*, pages 19–31, Washington USA. American Geophysical Union.

Enting, I. G. (2002). *Inverse Problems in Atmospheric Constituent Transport*. CUP, Cambridge, UK.

Enting, I. G. and Law, R. M. (2002). *Characterising historical responsibility for the greenhouse effect*. CSIRO Atmospheric Research Technical Paper no. 41. CSIRO, Australia. Available from:
http://www.dar.csiro.au/publications/enting_2002a.pdf .

Enting, I. G., Trudinger, C. M., and Francey, R. J. (1995). A synthesis inversion of the concentration and δ^{13}C of atmospheric CO_2. *Tellus*, 47B:35–52.

Enting, I. G., Trudinger, C. M., Francey, R. J., and Granek, H. (1993). Synthesis inversion of atmospheric CO_2 using the GISS tracer transport model. Tech. Paper No. 29, CSIRO Div. Atmos. Res.

Falkowski, P., Scholes, R. J., Boyle, E., Canadell, J., Canfield, D., Elser, J., Gruber, N., Hibbard, K., Höberg, P., Linder, S., Mackenzie, F. T., Moore III, B., Pedersen, T., Rosenthal, Y., Seitzinger, S., Smetacek, V., and Steffan, W. (2000). The global carbon cycle: A test of our knowledge of the earth as a system. *Science*, 290:291–296.

Farman, J. C., Gardiner, B. G., and Shanklin, J. D. (1985). Large losses of total ozone in Antarctica reveal ClO_x/NO_x interaction. *Nature*, 315:207–201.

Feder, J. and Aharony, A., editors (1990). *Fractals in Physics: Essays in Honour of Benoit B. Mandelbrot*. North Holland (Elsevier), Amsterdam.

Fisher, M. E. (1974). The renormalization group in the theory of critical phenomena. *Rev. Mod. Phys.*, 46:597–616.

Gallagher, R. and Appenzeller, T. (1999). Beyond reductionism. *Science*, 284:79.

Ganachaud, A. and Wunsch, C. (2000). Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. *Nature*, 408:453–457.

Goosse, H. and Fichefet, T. (1999). Importance of ice-ocean interactions for the global circulation: a model study. *J. Geophys. Res.*, 104C:23337–23355.

Gould, S. J. (1989). *Wonderful Life: The Burgess Shale and the Nature of History*. Penguin, London.

Gruber, N., Gloor, M., Feely, R., Roedenback, C., Sabine, C., and Sarmiento, J. (2001). Air-sea fluxes of pre-industrial and anthropogenic CO_2 determined by inverse modelling of ocean carbon data. In Organizing Committee, editor, *Sixth International Carbon Dioxide Conference, Extended Abstracts*, pages 1039–1042.

Grübler, A. and Nakicenovic, N. (2001). Identifying dangers in an uncertain climate. *Nature*, 412:15.

Hargreaves, J. C. and Annan, J. D. (2002). Assimilation of paleo-data in a simple Earth system model. *Climate Dynamics*, 19:371–381. doi: 10.1007/s00382–002–0241–0.

Hasselmann, K. (2002). Is climate predictable? In Bunde, A., Kropp, J., and Schellnhuber, H. J., editors, *The Science of Disasters: Climate Disruptions, Heart Attacks, and Market Crashes*, chapter 4, pages 140–169. Springer-Verlag, Berlin.

Hulme, M. (2000). Choice is all. *New Scientist. 4 November, 2000*, pages 56–57.

Kadanoff, L. P. (2001). Turbulent heat flow: Structures and scaling. *Physics Today*, 54(8):34–39.

Knorr, W. and Heimann, M. (1995). Impact of drought stress and other factors on seasonal land biosphere CO_2 exchange studied through an atmospheric tracer transport model. *Tellus*, 47B:471–489.

Kropp, J., Zickfeld, K., and Eisnack, K. (2002). Assessment and management of critical events: The breakdown of marine fisheries and the North Atlantic Thermohaline Circulation. In Bunde, A., Kropp, J., and Schellnhuber, H. J., editors, *The Science of Disasters: Climate Disruptions, Heart Attacks, and Market Crashes*, chapter 6, pages 192–216. Springer-Verlag, Berlin.

Kruijt, B., Dolman, A. J., Lloyd, J., Ehleringer, J., Raupach, M., and Finnigan, J. (2001). Assessing the regional carbon balance: Towards an integrated, multiple constraints approach. *Change*, 56 (March–April 2001):9–12.

Lavis, D. A. and Bell, G. M. (1999a). *Statistical Mechanics of Lattice Systems 1. Closed-form and Exact Solutions*. Springer-Verlag, Berlin.

Lavis, D. A. and Bell, G. M. (1999b). *Statistical Mechanics of Lattice Systems 2. Exact, Series and Renormalization Group Methods*. Springer-Verlag, Berlin.

Law, R. M., Rayner, P. J., Steele, L. P., and Enting, I. G. (2002). Using high temporal frequency data for CO_2 inversions. *Global Biogeochem. Cycles*, page doi:10.1029/2001GB001593.

Lenton, T. M. (1998). Gaia and natural selection. *Nature*, 394:439–447.

Lorenc, A. (1986). Analysis methods for numerical weather prediction. *Q. J. Roy. Meteorol. Soc.*, 112:1177–1194.

Lorenz, E. N. (1964). Irregularity: A fundamental property of the atmosphere. *Tellus*, 36A:98–110.

Lorenz, E. N. (1972). Predictability: Does the flap of a butterfly's wings in Brazil set off a tornado in Texas? [Lecture at AAAS meeting. Reprinted in E. Lorenz (1993) *The Essence of Chaos*. (UCL Press: London)].

Lorenz, E. N. (1993). *The Essence of Chaos*. UCL Press, London.

Lovelock, J. (1979). *Gaia: A New Look at Life on Earth*. OUP, Oxford.

Lovelock, J. E. and Margulis, L. (1974). Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis. *Tellus*, 26:2–10.

Mandelbrot, B. B. (1977). *Fractals: Form Chance and Dimension*. W.H. Freeman, San Francisco.

May, R. (1974). Biological populations with nonoverlapping generations: Stable points, stable cycles, and chaos. *Science*, 186:645–647.

McMichael, A. J. (2001). *Human Frontiers, Environments and Disease*. CUP, Cambridge, UK.

Melillo, J. M., Prentice, I. C., Farquhar, G. D., Schulze, E.-D., and Sala, O. E. (1996). Terrestrial biotic responses to environmental change and feedbacks to climate. In Houghton, J. T., Filho, L. G. M., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K., editors, *Climate Change 1995: the Science of Climate Change*, pages 445–481. Published for the IPCC by CUP, Cambridge, UK.

Ménard, R. and Chang, L.-P. (2000). Stratospheric assimilation of chemical tracer observations using a Kalman filter. Part II. χ^2 validated results and analysis of variance and correlation dynamics. *Monthly Weather Rev.*, 128:2671–2686.

Ménard, R., Cohn, S. E., Chang, L.-P., and Lyster, P. M. (2000). Stratospheric assimilation of chemical tracer observations using a Kalman filter. Part I. Formulation. *Monthly Weather Rev.*, 128:2654–2671.

Mitchell, J. F. B., Karoly, D. J., Hegerl, G. C., Zwiers, F. W., Allen, M. R., and Marengo, J. (2001). Detection of climate change and attribution of causes. In Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., editors, *Climate Change 2001: The Scientific Basis*, pages 695–738. Published for the IPCC by CUP, Cambridge, UK.

NASA (1986). Earth system science: A program for global change.

Oeschger, H., Siegenthaler, U., Schotterer, U., and Gugelmann, A. (1975). A box diffusion model to study the carbon dioxide exchange in nature. *Tellus*, 27:168–192.

Pittock, A. B., Jones, R. N., and Mitchell, C. D. (2001). Probabilities will help us plan for climate change. *Nature*, 413:249.

Prinn, R. G. (2000). Measurement equation for trace chemicals in fluids and solution of its inverse. In Kasibhatla, P., Heimann, M., Rayner, P., Mahowald, N., Prinn, R., and Hartley, D., editors, *Inverse Methods in Global Biogeochemical Cycles*, volume 114 of *Geophysical Monograph*, pages 3–18, Washington USA. American Geophysical Union.

Rayner, P. J. (2001). Atmospheric perspectives on the ocean carbon cycle. In Schulze, E.-D., Heimann, M., Harrison, S., Holland, E., Lloyd, J., Prentice, I. C., and Schimel, D., editors, *Global Biogeochemical Cycles in the Climate System*. Academic, San Diego.

Rind, D. (1999). Complexity and climate. *Science*, 284:105–107.

Rodgers, C. D. (1976). Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation. *Rev. Geophys. Space Phys.*, 14:609–624.

Rodgers, C. D. (2000). *Inverse Methods for Atmospheric Sounding: Theory and Practice*. World Scientific, Singapore.

Santer, B. D., Wigley, T. M. L., Barnett, T. P., and Anyamba, E. (1996). Detection of climate change and attribution of causes. In Houghton, J. T., Filho, L. G. M., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K., editors, *Climate Change 1995: The Science of Climate Change*, pages 407–443. Published for the IPCC by CUP, Cambridge UK.

Scheffer, M., Carpenter, S., Foley, J., Folke, C., and Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, 413:591–596.

Schneider, S. (2001). What is ‘dangerous’ climate change? *Nature*, 411:17–19.

Siedler, G., Church, J., and Gould, J., editors (2001). *Ocean Circulation and Climate: Observing and Modelling the Global Ocean*. Academic, San Diego.

Sornette, D. (2000). *Critical Phenomena in Natural Sciences*. Springer-Verlag, Berlin.

Stammer, D., Wunsch, C., Fukumori, I., and Marshall, J. (2002). State estimation improves prospects for ocean research. *EOS: Trans. AGU*, 83 (27):289 and 294–5.

Stocker, T. F., Clarke, G. K. C., Le Treut, H., Lindzen, R. S., Meleshko, V. P., Mugara, R. K., Palmer, T. N., Pierrehumbert, R., Sellers, P. J., Trenberth, K. E., and Willebrand, J. (2001). Physical climate processes and feedbacks. In Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linder, P. J., Dai, X., Maskell, K., and Johnson, C. A., editors, *Climate Change 2001: The Scientific Basis*, pages 417–470. Published for the IPCC by CUP, Cambridge, UK.

Sundquist, E. T. (1985). Geological perspectives on carbon dioxide and the carbon cycle. In Sundquist, E. T. and Broecker, W. S., editors, *The Carbon Cycle and Atmospheric* CO_2*: Natural Variations Archean to Present*, Geophysical Monograph 32, pages 5–59. AGU, Washington.

Tauber, U. C., Akkineni, V. K., and Santos, J. E. (2002). Effects of violating detailed balance on critical dynamics. *Phys. Rev. Lett.*, 88:045702.

Trudinger, C. M. (2000). *The Carbon Cycle over the Last 1000 Years Inferred from Inversion of Ice Core Data*. Ph.D. thesis, Monash University. Available from: *http://www.dar.csiro.au/publications/Trudinger_2001a0.htm* .

Trudinger, C. M., Enting, I. G., Francey, R. J., Etheridge, D. M., and Rayner, P. J. (1999). Long-term variability in the global carbon cycle inferred from a high-precision CO_2 and δ^{13}C ice-core record. *Tellus*, 51B:233–248.

Twomey, S. (1977). *Introduction to the Mathematics of Inversion of Remote Sensing and Indirect Measurements*. Elsevier, Amsterdam.

van der Waals, J. D. (1873). *Over de Continuiteit van der Gas- en Vloeistoftoestand*. Doctoral thesis, Leiden.

Weisse, R., Mikolajewicz, U., Sterl, A., and Drijfhout, S. (1999). Stochastically forced variability in the Antarctic Circumpolar Current. *J. Geophys. Res.*, 104:11049–11064.

Wigley, T. M. L. and Barnett, T. P. (1990). Detection of the greenhouse effect in the observations. In Houghton, J. T., Jenkins, G. J., and Ephraum, J. J., editors, *Climate Change: The IPCC Scientific Assessment*, pages 239–255. Published for the IPCC by CUP, Cambridge, UK.

Wolfram, S. (2002). *A New Kind of Science*. Wolfram Press.

Woodwell, G. M. and MacKenzie, F. T., editors (1995). *Biotic Feedbacks in the Global Climatic System: Will the Warming Feed the Warming?* OUP, New York.

Wu, F. Y. (1978). Percolation and Potts model. *J. Statist. Phys.*, 18:115–123.

Wunsch, C. (1996). *The Ocean Circulation Inverse Problem*. CUP, Cambridge, UK.

Ziemelis, K. (2001). Nature insight: Complex systems. *Nature*, 410:241.

Appendix: The statistical physics background

A number of ideas in complex systems science have their origin in studies of the lattice statistical mechanics of cooperative phase transitions. The field of statistical mechanics involves the derivation of bulk thermodynamic properties (the macrostate) from underlying statistical characterisations of microstates. The latter are represented as interacting components, with probabilities expressed in terms of interaction energies and temperature. Sornette (2000) gives an overview of lattice statistics in the context of complex systems. A technical account of lattice statistical mechanics is given by Lavis and Bell (1999a; 1999b).

Some of the key results are:

- Systems of simple components with simple interactions can undergo spontaneous ordering at low temperatures.
- A phase transition will occur between the low-temperature ordering and high-temperature regimes where the system is disordered.
- The transition may be ‘first-order’, i.e. discontinuous disappearance of order, or ‘continuous’ where the order goes continuously to zero.
- The disappearance of order in continuous transitions is generally characterised by power-law behaviour, in the order and other thermodynamic quantities. This corresponds to ‘fractal’ behaviour (Mandelbrot, 1977) in the microstates. Such states exhibit divergent responses to forcing and large spontaneous fluctuations. In regions away from the critical, disordered at high temperatures and ordered at low temperatures, spatial correlations decay exponentially. However at criticality power-law decay of correlations occurs.
- In many systems, the types of critical behaviour (i.e. the values of the power-law exponents) depend only on the symmetry of the interacting components and the bulk dimensionality of the system. This characteristic is known as ‘universality’.
- However, systems with competing interactions can exhibit much more diverse critical behaviour.
- Much of statistical mechanics is based on Gibbs probabilistic formulation with the probabilities of microstates proportional to $\exp[-E/kT]$ where E is the energy, T is the absolute temperature and k is Bolztmann’s constant. Many lattice statistics systems that lie outside the can nevertheless be mapped onto this formalism, by defining their probabilities in terms of effective energies. Such equivalences provide both conceptual unification and, on occasion, computational advantages. One example is the relation (Wu, 1978) connecting a limiting case of a q-state statistical mechanics model in a regular lattice to the percolation model which describes the connectivity of a lattice with randomly occupied edges. This is the basis for noting, in Section 1, that *the irregular connections [identified as a characteristic of complex systems] may not be an essential aspect if there are other sources of randomness*.

There are a number of classes of technique that have been developed for investigating such cooperative phase transitions:

exact solutions In some very special cases, exact solutions of non-trivial lattice statistics problems are possible (Baxter, 1982).

power series expansions These expand the thermodynamic quantities as power series, almost always expanding about either a fully-ordered state (zero temperature) or a completely random state (infinite temperature) (Lavis and Bell, 1999b; Chapter 7).

statistical closures These involve averaging aspects of the statistical distributions of the microstates. At least in low dimensions (2 or 3) they frequently give incorrect values of the power-law exponents (Lavis and Bell, 1999a).

renormalisation group Renormalisation group techniques operate by defining the way in which effective interaction probabilities change under change of length scale. Since the probabilities take the form of Boltzmann weights, i.e. functions of energy and temperature, changing the probabilities corresponds to transforming the set of interaction energies. The power-law behaviour arises from the limiting (fixed-point) characteristics of these transformations (Fisher, 1974).

Monte carlo simulations These act to simulate the statistical distributions by working directly from the microstate probabilities (Binder and Heermann, 1988).

Some years ago, self-organised criticality appeared as new paradigm, from models termed ‘sand-pile models’(Bak et al., 1987, 1988; Bak, 1996) see also (Sornette, 2000; Chap. 15). These exhibited criticality spontaneously rather than at special isolated values of a control parameter such as temperature. This has led to a number of exaggerated claims, including that implicit in the title of Bak’s book: *How Nature Works* (Bak, 1996). Similarly, Buchanan’s claim that *the ubiquity of the critical state may well be considered the first really solid discovery of complexity theory* (Buchanan, 2000) seems greatly overstated. At the very least, the diversity (noted above) of critical behaviour in systems with competing interactions means that very little can be inferred about a system merely from observation of power-laws.

Given this background it is interesting to speculate on the future influence of statistical physics on complex systems science. Some of the main possibilities are:

Conceptual This has been the main role to date. There would seem to be a continuing role since much of the ‘complex systems’ discussion picks up on only a small part of the diversity exhibited by lattice statistics models.

Special submodels On occasion, special aspects of Earth System science may be addressable by specific lattice statistics models. An example is the application of the percolation model to the trapping of air bubbles in polar ice (Enting, 1985, 1993).

Techniques The lattice statistics techniques listed above vary in their applicability to more general complex systems. Exact solutions have only restricted applicability, even in highly structured lattice systems. Statistical closures are widely applicable but near critical points they are poor approximations and sequences of higher-order closures are slowly convergent.

Toy models This is really an extension of the 'conceptual' influence. It is the development of highly-simplified models to explore the generic characteristics of complicated (and/or complex) systems. An example of such a generic question is the extent to which complex adaptive systems are inherently different from other complex systems. This is of considerable importance in considerations of ecosystem development during global change.

Two new results that may point the way to extensions of statistical mechanics techniques into complex systems studies are:

- Egolf (2000) suggests that coarse-graining of coupled chaotic systems, far from equilibrium, can lead to characterisations that can be analysed using the techniques of equilibrium statistical mechanics.
- Tauber at al. (2002) suggest that, apart from 'hard constraints' imposed by conservation laws, the critical behaviour of dynamically evolving systems does not produce new types of critical behaviour from a failure of the condition of detailed balance in the evolution.

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