

Complex Models. EBMs are straightforward and, especially when one moves to the 1-D case, give qualitative understanding of various important phenomena. But this transparency is achieved by omission of a multiplicity of factors. For example, because they deal with energy flows, the only thing that comes out of them is temperature. Other climatic variables, for example, the movement of air masses, must either be ignored or, in the case of 1-D models, inferred by *ad hoc* arguments. Not surprisingly, “real” climate models – the ones used to forecast global warming – are far more complicated. Of these, we note the following:

- *Radiative convective models* (RCMs) perform detailed calculations of radiative transfer, the Gain and Loss functions in Figure 1. To this end, they divide the atmosphere into layers, which complication allows for the construction of vertical temperature profiles.
- *General circulation models* (GCMs) are more ambitious – the object being to describe world wide atmospheric and/or oceanic circulation. As such, they compute circulation patterns from first physical principles, integrating the appropriate equations of motion forward in time from specified initial conditions. Almost invariably, GCMs are three dimensional, in which regard the atmosphere (ocean) is divided into cells within which the various physical processes operate homogeneously. The cells, in turn, are coupled by transfer of the appropriate quantities – mass, energy, momentum, *etc.* – in much the same way that 1-D EBMs couple latitudinal bands by Fickian diffusion.
- *Unified earth system models* (UESMs). Historically, GCMs derive from models used to generate meteorological forecasts. With the passage of time – and the availability of ever-faster computers – they have come to include various “add-ons.” The result is today’s unified earth system models (Figure 6) in which a coupler program transfers quantities from one subsystem to another. Often, complexity of the add-ons exceeds that of the core. Importantly, UESMs are *computationally bound*. By this is meant that run-length (number of days / years simulated) and resolution (cell size) are limited by the availability of CPU cycles.¹

Parameterization. All climate models include adjustable parameters. Their presence results from the necessity of averaging over time and space (within cells) and by the omission or simplification of subsystems. As Covey (1989) remarked,

“Not even an increase in computing speeds of several orders of magnitude will permit models to encompass spatial scales from millimeters to thousands of kilometers, time scales from seconds to millenia, and to treat in detail subsystems as varied as the atmos-

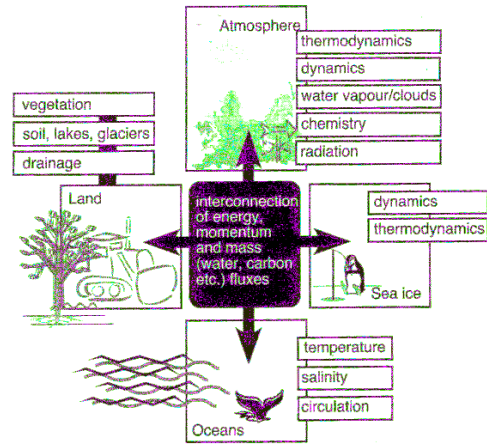


Figure 6. Ocean-land-atmosphere-sea ice model. The four submodels are connected by a “coupler” program that transfers fluxes between them. From McGuffie and Henderson-Sellers (2005).

¹ Analogously, is the interesting, and so far as I am aware, currently unresolved, question as to whether or not the human brain is computationally bound [REF].

phere, the oceans, glaciers and all the components of the biosphere. Consequently, there will always be a need for parameterizations and inevitably some of the parameterizations will be of doubtful validity.”

That was back in 1989, but as McGuffie and Henderson-Sellers (2005) observed a decade and a half later, a paucity of CPU cycles remains, and apparently will remain, a reality with which the modeling community must live (Figure 7).

It should be emphasized that there is nothing wrong or even unusual about this. The whole point of modeling is to reduce a system to its essentials, or, to put it another way, to determine what those essentials are.² Indeed, were it possible to reproduce the entirety of the world’s complexity *in silico*,³ the result would be to substitute a model one doesn’t understand for a system one doesn’t understand.⁴ In short, the validity (and practical utility) of climate models depends on their ability to generate falsifiable predictions that can withstand observational scrutiny.

Forcings. Increasing greenhouse gas concentrations – the result of human activity – is called as *anthropogenic forcing*, “Anthropogenic,” of course, refers to the source the additions; “forcing,” to the idea that an external perturbation is causing the system to deviate from its natural behavior. In the case of human activity, the meaning of the word, “natural” – *terra sine homine* – is easy to infer; likewise with variations in the earth’s orbit and orientation (see below) which may be regarded as external to the planet and its biota. But climatologists speak of other forcings – volcanic eruptions, for example, which are part of the system, but, often, not of the models. In short, whether a process is viewed as part of the system or an external forcing often reflects what the modeler *can*, as a matter of practicality, or *chooses*, as a matter of outlook, to model. This brings us back to the system-environment distinction discussed in Lecture I.

² The way one goes about this, of course, is by inducing predictions that are then tested with experiments or observations. When, as is often the case, the predictions fail, one goes back to the workbench and reformulates the model. To be useful, the new version must resolve the previous discrepancies and generate new predictions that themselves can be put to the test.

³ A recent, and arguably pretentious, addition to the more familiar terms, *in vitro* and *in vivo*.

⁴ See, for example, the allegory, *On Exactitude in Science*, by Jorge Luis Borges (1998).

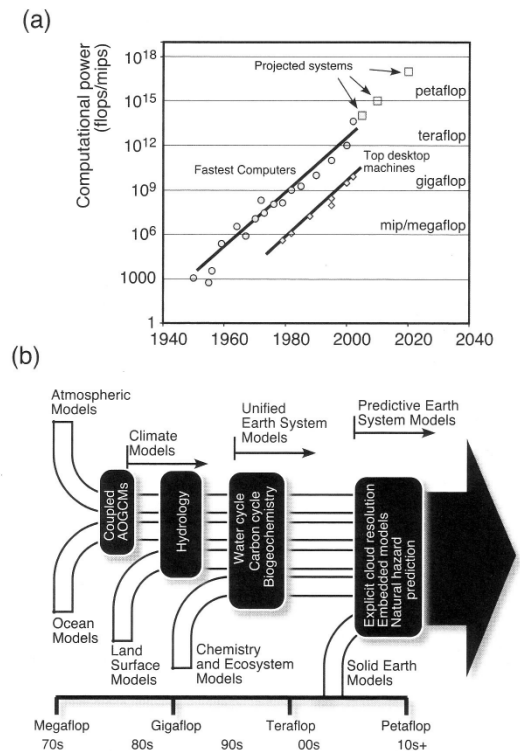


Figure 7. Computer performance (a) and dependence of feasible model complexity thereon (b). From McGuffie and Henderson-Sellers (2005).

Of course, such decisions are not wholly arbitrary. As previously discussed, time scales matter. In particular, if time scales are disparate, one proceeds in one of two fashions:

1. If it is the short-term that is of interest, one fixes the values of the slow variables, imagining them to be constant.
2. If it is the long-term that matters, one assumes the fast variables are “slaved” to the slow ones, *i.e.*, one imagines fast subsystems to be in approximate equilibrium with the slow ones.

In this spirit, variations in solar flux due to changes in the earth’s orbit and orientation – so-called “Milankovitch cycles” – are treated as either constants (interest in the near-term) or as “drivers” (interest in the long-term) of the climate system. This is because, the time scales – 100,000 years (orbital eccentricity), 40,000 y (axial tilt) and 23,000 y (precession) – are long, relative to those on which short-term climatic change occurs. Interestingly, Milankovitch frequencies show up in ice-core data (Figure 8), suggesting that orbital forcing has played a role in comings and goings of the ice during the past million years. Also interesting is the fact that these frequencies account for only a fraction of the total variance – *i.e.*, were they the whole story, the power spectrum in Figure 9 would have prominent peaks rising out of the background. One explanation for the actual form of the spectrum is observational error; another, that the climate fluctuates on many time scales, which, as shown in Figure 9, it most certainly does.

The Consensus View of Climate Change. Representative of the so-called “consensus view” of climate change is a recent article by Hansen *et al.* (2006). The principal claims are as follows:

1. Greenhouse gas concentrations (Figure 10) and global temperatures (Figure 11) have been rising, at least since the onset of the industrial revolution (Figure 12).

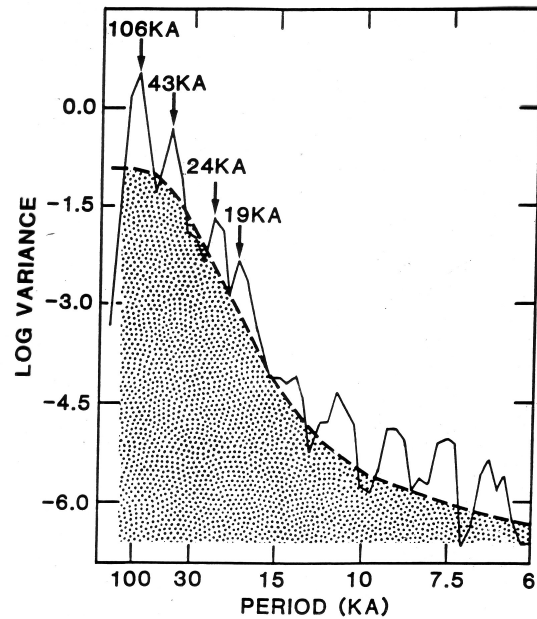


Figure 8. Power spectrum based on oxygen-isotope ratios (proxy variable for temperature) from deep-sea ice cores. The peaks at 106 and 43 ka are consistent with Milankovitch forcing. Redrawn from Imbrie and Imbrie (1979).

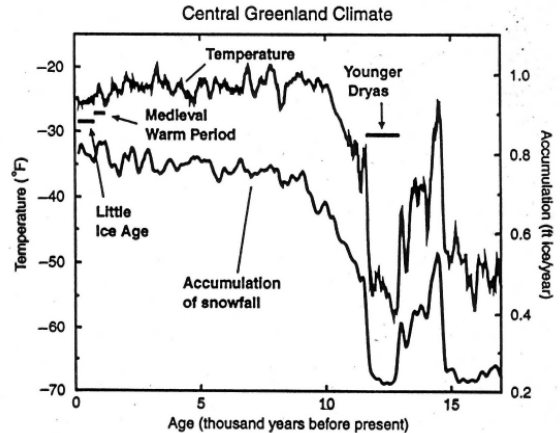


Figure 9. Temperature and snowfall records reconstructed from Greenland ice cores. The Little Ice Age and Medieval Warm Period are dwarfed by earlier fluctuations such as the Younger Dryas. From Alley (2000).

2. The former drives the latter as indicated by correlated fluctuations in CO₂ concentration and reconstructed temperatures over hundreds of thousands of years.
3. Increasing concentrations of greenhouse gases are the result of *anthropogenic forcing*.
4. Continued anthropogenic forcing will lead to further increases in temperature, rising sea levels, widespread desertification, *etc.* (Figure 13).

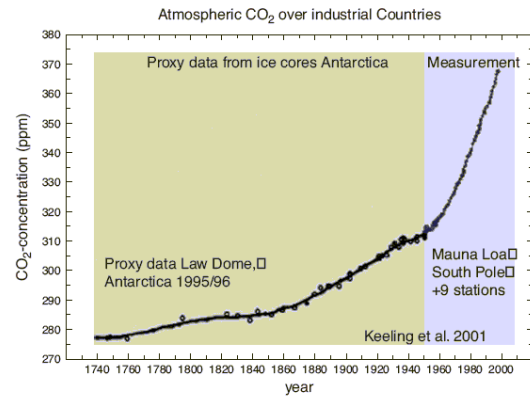


Figure 10. Reconstructed and measured concentrations of atmospheric CO₂ from Beck (2007) after Keeling *et al.* (2001)

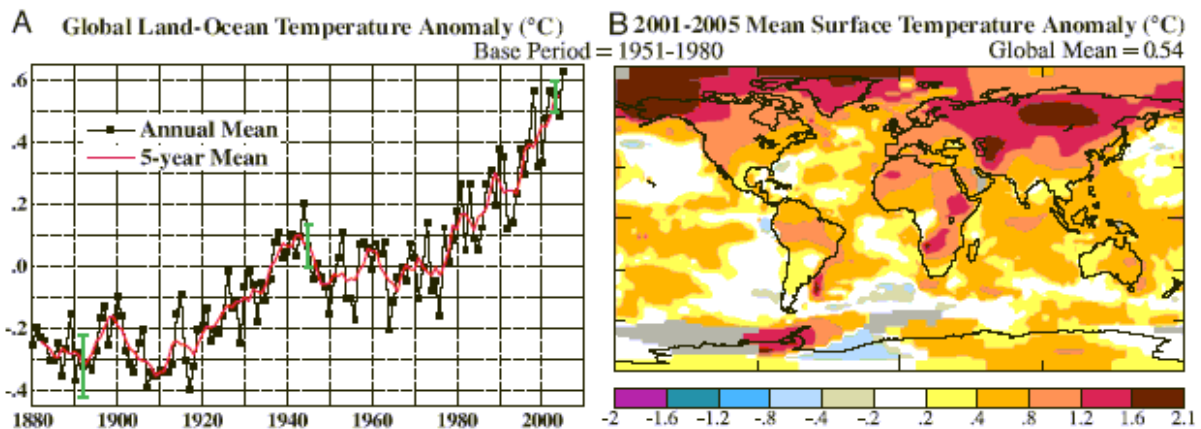


Figure 11. Rising global temperatures (left) and current (2001-2005) surface temperature anomaly. From Hansen *et al.* (2006)

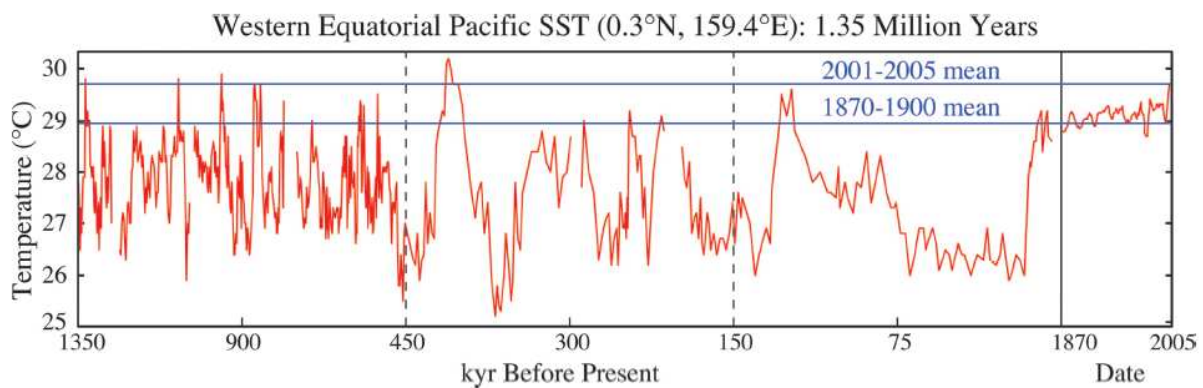


Figure 12. Current temperatures compared with paleo reconstructions. From Hansen *et al.* (2006). According to the figure, current sea surface temperatures are the highest in over 100 ka.

Problems. Objections to the consensus view include the following:

1. The CO₂ curve in Figure 10 is inaccurate. Based on an exhaustive review of pre-1960's, chemical analyses, Beck (2007) argues that the true picture for northern hemisphere atmospheric CO₂ is as shown in Figure 14. In so doing, he rejects the IPCC point of view, which is that prior to the industrial revolution, atmospheric carbon dioxide was more or less constant at 280 ppm. Beck further disputes claims that pre-spectroscopic data are unreliable, claiming, to the contrary that they are,

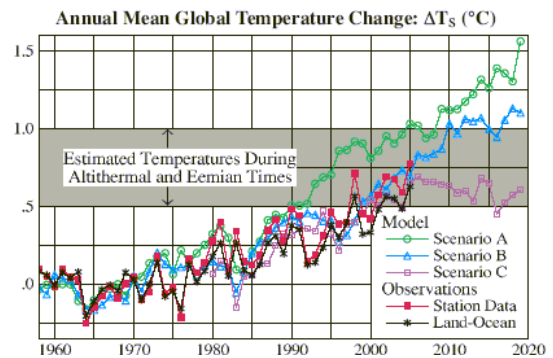


Figure 13. Predicted increases in global temperature according to three models. From Hansen *et al.* (2006),

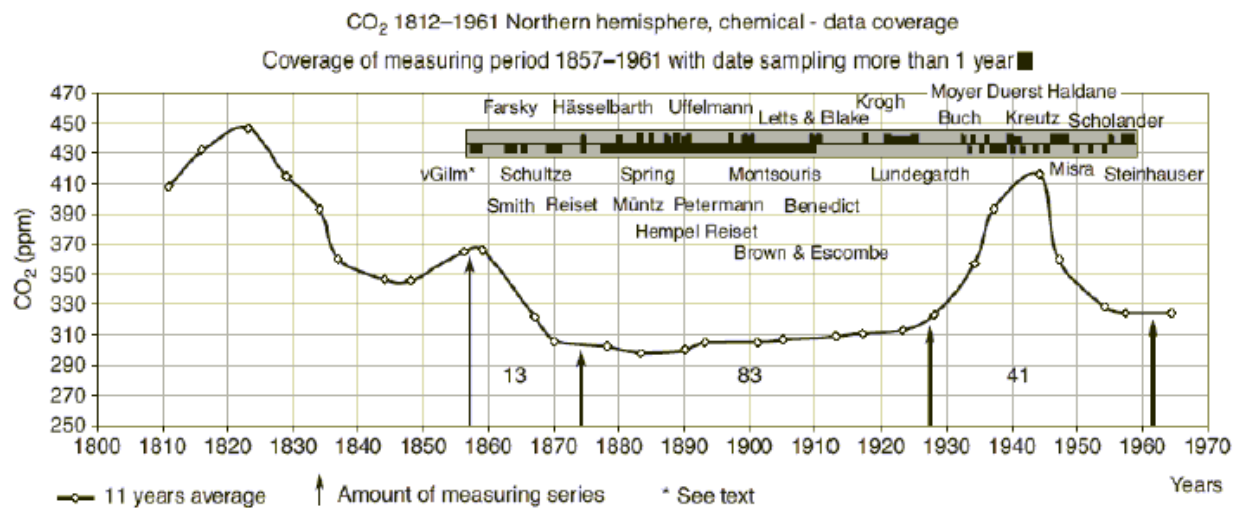


Figure 14. Beck's (2007) reconstructed chemical record of atmospheric CO₂.

accurate to within 5%.

2. Likewise, “hockey-stick” (Mann, *et al.*, 1998, but see McIntyr and McKittrick, 2003) reconstructions of northern hemisphere temperatures are neglect the down-up pattern (1000 AD to the present) shown in Figure 9, with the Little Ice Age first driving Greenland Vikings to switch (Figure 15) from a diet of milk and meat to one of seal and fish (Arneborg, *et al.*, 1999) and later to abandon their settlements altogether.
3. While, atmospheric CO₂ and temperatures are correlated over long periods, it is apparent that, at least in some cases, increasing temperatures *precede* increasing concentrations of CO₂ (Caillon, *et al.*, 2003).
4. Historical, especially pre-industrial, variations in temperature also correlate (Figure 16) with variations in solar activity (Solanki, 2002; Scafetta and West, 2006), in which regard,

Svensmark and Friss-Christensen (1997; Svensmark, 1998) have proposed a novel mechanism involving cosmic rays and cloud formation

- Climate models are unreliable – in part because of the parameterizations noted above. More generally, they ignore possible sources of negative feedback – for example, decreasing cirrus cloud cover (which increases long wave re-radiation) in response to increasing temperature (Lindzen *et al.*, 2001).

Turbulence and Chaos. The most economical interpretation of the historical record and paleo reconstructions taken together is that the climate fluctuates on all possible time scales. This is the

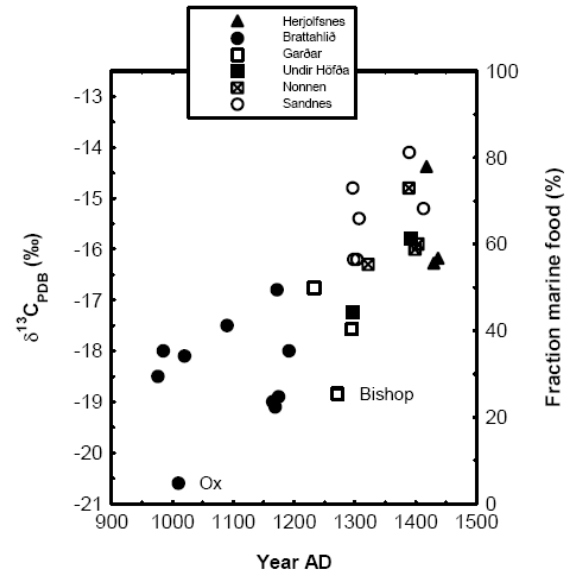


Figure 15. Changing diet of the Greenland Vikings. From Arneborg *et al.* (1999).

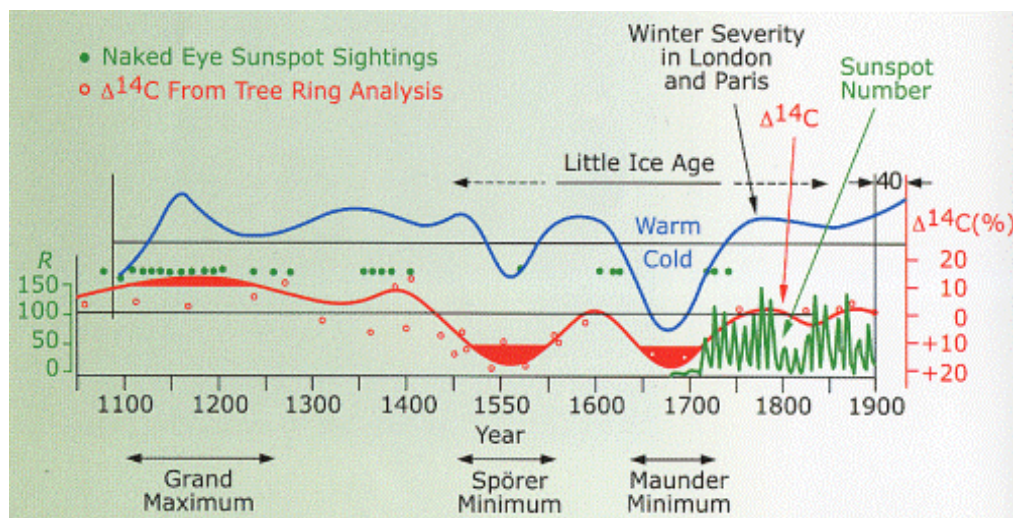


Figure 16. Pre-industrial solar activity and northern hemisphere temperatures. From a NASA press release. See also Scafetta and West (2006),

definition of turbulence, and it raises two questions: The first is the origin of the fluctuations – to which one can point either to solar forcing, which is itself turbulent, or to the effects of intrinsic feedbacks and / or delays.⁵ The second is the origin of quasi-cyclic behavior, in which regard we remark that chaotic motions are characterized by the transient shadowing of periodic orbits with the stability properties of saddles – see, for example, Schaffer *et al.* (1993) and references therein. It is the author's opinion that contemporary climate models, to the extent that they lack this topology, will ultimately prove wanting.

⁵ These explanations are, of course, not mutually exclusive.

Self-Correction and Science. Scientists often speak of the self-correcting nature of the enterprise in which they engage. But history teaches that corrections are often preceded by protracted periods of conformity, *e.g.*, Powell (2001). This is especially the case when science gets conflated with ideology – see, for example, Gould (1981) and Roll-Hansen (2005) – as is arguably the case in the present case.

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