

Lecture 0

A very brief introduction

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Climate variability results from a very diverse set of physical phenomena and occurs on a very wide range of time scales. It is difficult to envision a single model, complex as it might be, which could explain, simulate or predict all sources of climate variability. It is therefore simple models, that concentrate on a single or a few phenomena and on some limited range of time scales, that have had the most success in explaining the physics of climate variability. We start these lectures with a very brief gallery of examples of climate variability from very long time scales to shorter ones, and of a few climate toy models that are displayed without much of a discussion, as an introduction to the fuller review in the following lectures.

After this introduction, the following lectures discuss conceptual (toy) models of the El Nino - Southern Oscillation phenomenon (lectures 1-3), of the thermohaline circulation (lectures 4-5), and of glacial cycles (lectures 8-9) preceded by some basic concepts of climate dynamics (lectures 6-7). We conclude with a brief discussion of toy models of very early earth and planetary climates (lecture 10).

Climate variability exists on all time scales from seconds to billions of years, as shown in the schematic spectrum of Fig. 1. The last 60 Million years (Myr) show a gradual slow cooling, and a strong increase in variability over the past few millions of years (Fig. 2). Continuing to the more recent past, the Quaternary (last 2.6 Myr) glaciation record shows the glacial cycles and a significant change in the nature of these oscillations some 1 Myr ago (Fig. 3).

Focusing on the past 150,000 years, one sees a full glacial cycle (Fig. 4). On shorter-yet time scales, and focusing on the past 90 kyr or so, we can see Heinrich events (major iceberg discharges on a 7-10 kyr time scale), and Dansgaard-Oeschger oscillations (warm events in Greenland ice core records, 1000-1500 yr time scale, Fig. 5). The variability is clearly very dramatic in terms of both amplitude and abruptness of the observed climate changes. A record of the past 10,000 yr shows the Younger Dryas cold event interrupting the last deglaciation (Fig. 6), while the record during the past 500 years shows the “little ice age” (Fig. 7). Finally, on a time scale of a few years to decades, we see the North Atlantic Oscillation record (Fig. 8) and an El Nino record for the past 50 years (Fig. 9).

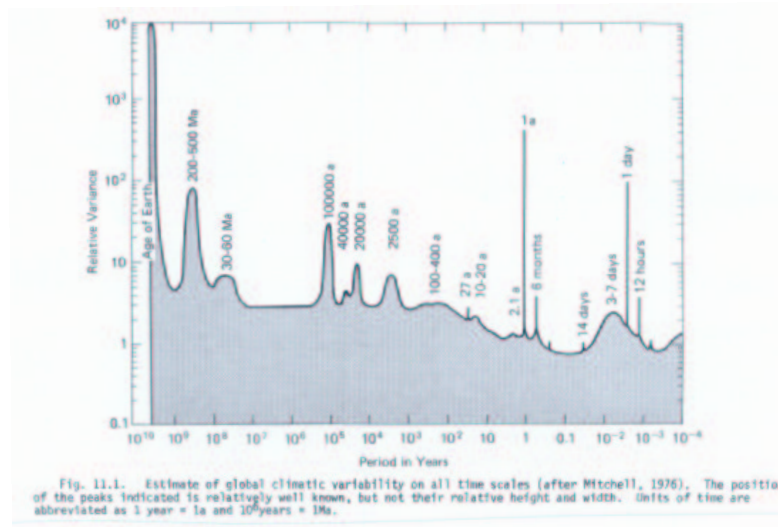


Figure 1: A schematic climate spectrum (Ghil and Childress Fig. 11.1).

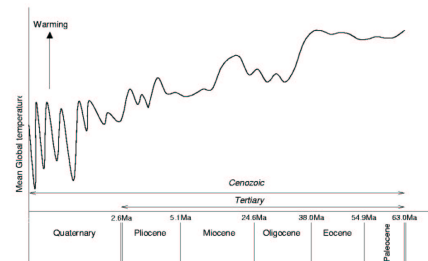


Fig 4.1 - General climatic trends through the Cenozoic, clearly demonstrating the overall cooling and increased climatic variability of the Quaternary. Based on Bradley (1985).

Figure 2: The past 60 Myr (Heslop 2001, <http://www.geo.uu.nl/~forth/David/chapter4.pdf>).

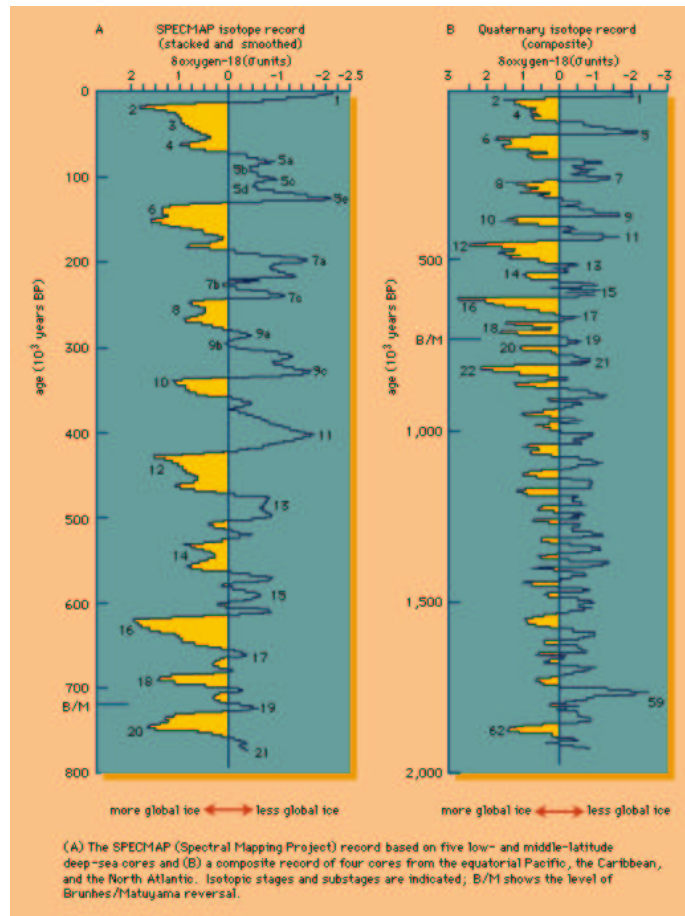


Figure 3: SPECMAP record of glacial cycles over the past 2Myr from ocean sediments.

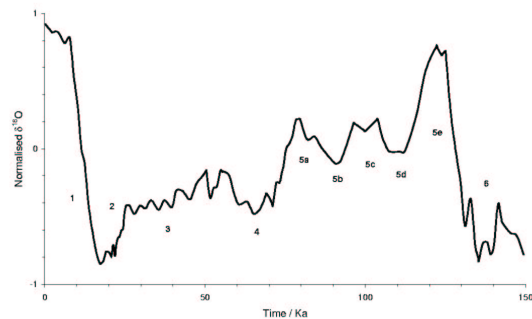


Fig 4.7 – Oxygen isotope stages for the past 150Ka in the Martinson et al (1987) stacked marine isotope record.

Figure 4: The past 150 kyr and isotopic stages (Heslop 2001, <http://www.geo.uu.nl/~forth/David/chapter4.pdf>).

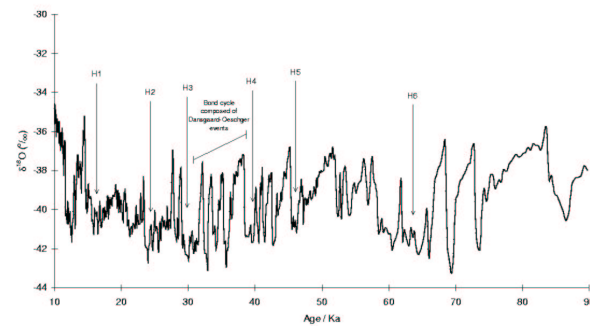


Fig 4.10 - $\delta^{18}O$ record from the GISP2 record demonstrating the grouped interstadial cooling events defined as Bond cycles. Each cooling phase is composed of a number of Dansgaard-Oeschger events that produce the characteristic asymmetric saw-tooth shape and is terminated by a cold Heinrich event, which are marked H in the figure.

Figure 5: An ice core (GISP) record of the past 90 kyr, showing Heinrich events (10 kyr time scale), and Dansgaard-Oeschger oscillations (1 kyr time scale), (Heslop 2001, <http://www.geo.uu.nl/~forth/David/chapter4.pdf>).

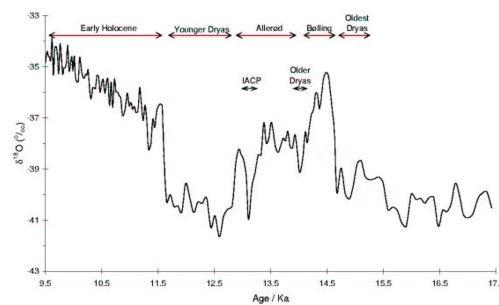


Fig 4.14 - Variations in $\delta^{18}O$ within the Lateglacial zone of the GISP2 ice-core. The resolution of this record is sufficient to show in detail all the chronozones previously defined by European pollen records. Based on Stuiver et al 1995.

Figure 6: A record of the period from 9 kyr before present (bp) to 17 kyr bp, and the Younger Dryas event (Heslop 2001, <http://www.geo.uu.nl/~forth/David/chapter4.pdf>).

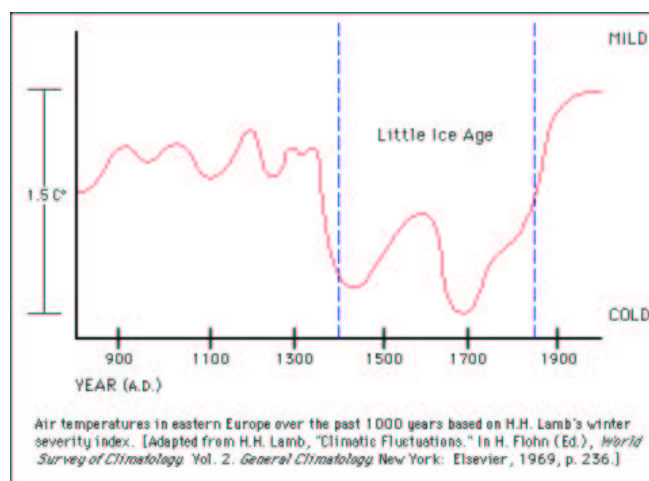


Figure 7: The little ice age...

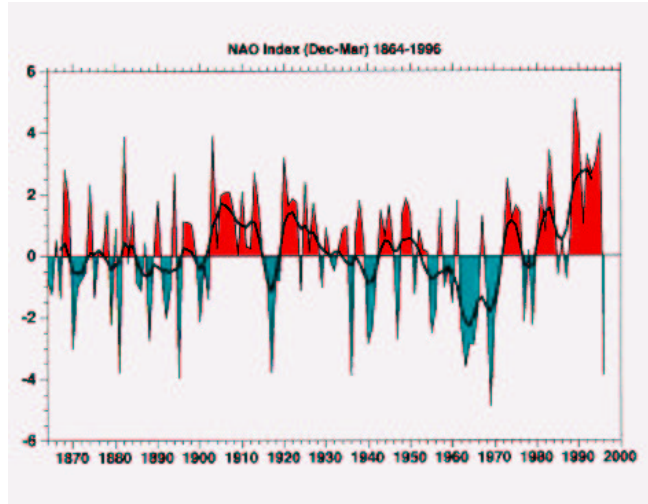


Figure 8: The NAO index from 1864 to 1996, defined as the difference in normalized pressure between Lisbon and Stykkisholmur, for the winter months, December-March. From “Atlantic Climate Variability” by Marshall and Kushnir, <http://geoid.mit.edu/accp/avehtml.html>.

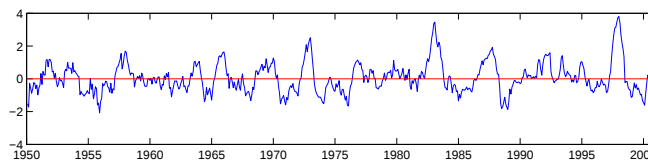


Figure 9: NINO3 record (averaged SST over the East Pacific: 5N-5S, 150W-90W), from 1950 to 2001.

The above gallery of climate variability examples, should make it clear that first, the climate system is tremendously complicated and second, that we are not likely to succeed in understanding it using a single model of all of the above phenomena and processes. Models used to study climate variability form a hierarchy, from general circulation models (GCMs) to toy models, roughly as follows:

1. General Circulation Models: 3D PDEs (based on the Navier-Stokes equations or similar) of the oceans and atmosphere, which require large computational resources and are not easy to decipher.
2. Intermediate models (Quasi Geostrophic, sometimes 2D; 2D continuous models in either longitude-latitude or latitude-depth; simplified reduced gravity layer models, etc):
3. Idealized toy (conceptual) models that highlight a single or a few physical mechanisms, and are more often than not derived heuristically, by guessing what the most dominant feedbacks are, rather than being derived rigorously from fuller models.

The focus of the following lectures is the third category, of toy models. These models, in spite of their heuristic derivation, have had a surprising success in explaining a variety of climate phenomena. Furthermore, the predictions of such highly simplified models have been confirmed numerous times by far more complex and realistic models. Let us briefly consider a few examples of such toy models in order to get an impression of the level of idealization they correspond to. Begin with a 0D energy balance model of the globally averaged temperature in which incoming radiation is partially reflected by the earth albedo and is balanced (at steady state) by long wave outgoing radiation

$$\frac{dT}{dt} = H_{\odot}^{\downarrow} \times (1 - \text{albedo}(T)) - \sigma T^4.$$

Some remarkable results may be obtained when considering specific dependences of the albedo on the temperature, as will be seen in lectures 6-9.

Proceed next to the Stommel two box [55] model of the thermohaline circulation (THC, Fig. 10). This model makes some simplifying assumptions that seem not only unjustified but possibly also unjustifiable. Yet, the model predictions of multiple equilibria and stability behavior of the THC have been confirmed by 3D ocean and coupled GCM results and have been shown to be remarkably robust (more in lectures 4-5).

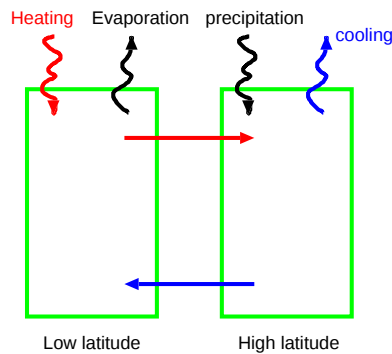


Figure 10: The Stommel two box model of the Thermohaline circulation

As a third and final example, consider a (nondimensional) delayed oscillator model of ENSO [56], to be further discussed in Lectures 1-3, in which the sea surface temperature of the East Pacific is affected by positive feedback term due to equatorial Kelvin wave propagation, by a delayed negative term due to equatorial Rossby waves, and using some simple cubic dissipation term

$$\frac{dT(t)}{dt} = T(t) - \alpha T(t - \delta_T) - T^3(t).$$

This simple model provides heuristic understanding of ENSO's dynamics that has led to many further interesting dynamical insights.

In general, toy models such as these, in spite of their lack of rigor, proved to be the most useful tool for understanding climate variability. Once a physical mechanism is understood within such an idealized toy model, the fuller intermediate models or GCMs may be used for a quantitative study of the proposed mechanism and for validation in a more realistic framework. Surprisingly, when the toy model results are checked using observations and fuller and more realistic models, the predictions of these toy models are often found correct as well as robust, making the study of such models worthwhile. That these trivial models are so successful in producing robust explanations for complex climate phenomena is nearly a miracle, possibly indicating that in spite of the complexity of the entire climate system, each separate time scale is governed by relatively simple low order dynamics.