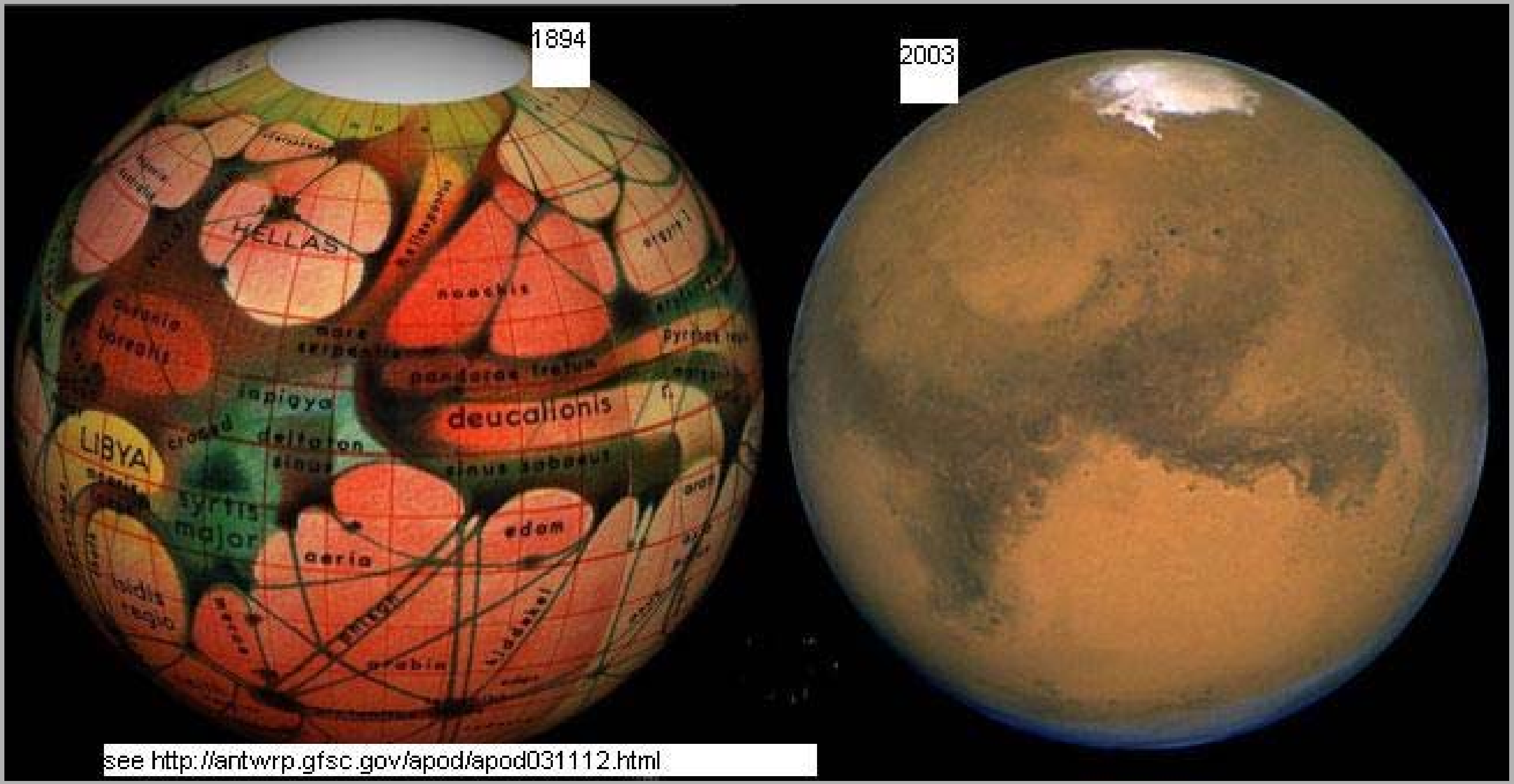
12.842 / 12.301 Past and Present Climate
Fall 2008

Randomness and Chaos in the Climate System

Human psychology leads people (scientists) to seek deterministic (predictable) causes for observed changes in the world. Nonetheless, one must remain alert for the possibility that much of the climate system may not actually be predictable beyond some rather short interval.

The problem is compounded by the evolutionary development of the human eye as a wonderful pattern recognition device. Patterns are seen everywhere, even when not real.



Classic example was the detection of “canali” on Mars in the late 19th and early 20th centuries.

A book on the subject is:
Kahneman, D., P. Slovic, A. Tversky
1982 Judgment Under Uncertainty: Heuristics and Biases 555pp. Cambridge Un. Press

Few people have an intuition for the behavior of noise processes, particularly those with a “memory”.

Hasselmann (1976, Tellus) gave the prototypical example. Consider an "ocean" which has a large heat capacity and so "remembers" the previous history of random temperature forcing by the atmosphere, so that ocean temperature might be computed as

$$\frac{dT}{dt} = q(t)$$

where $q(t)$ is totally random. Let’s make life simple by putting this equation into a discrete approximation as

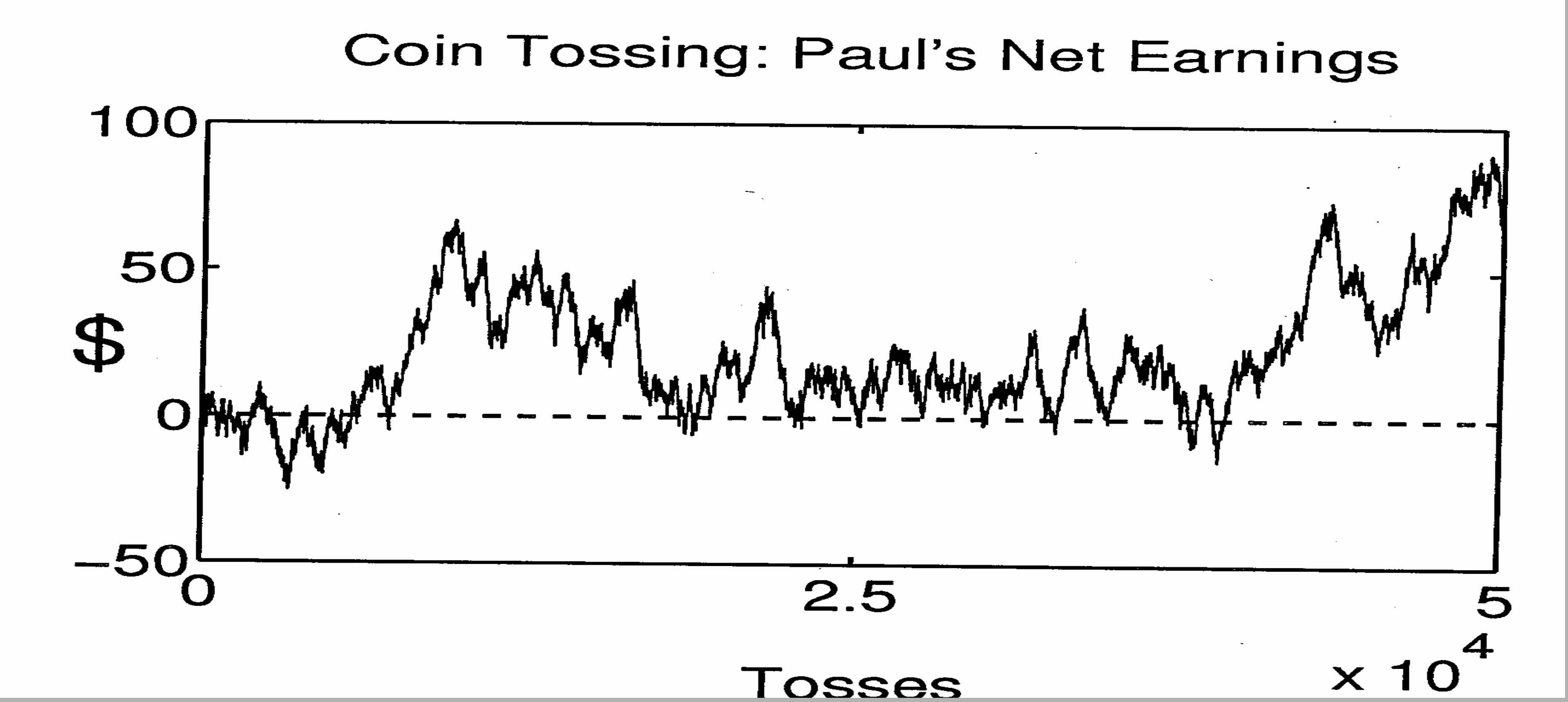
$$T(n\Delta t + \Delta t) - T(n\Delta t) = \Delta t q(n\Delta t)$$

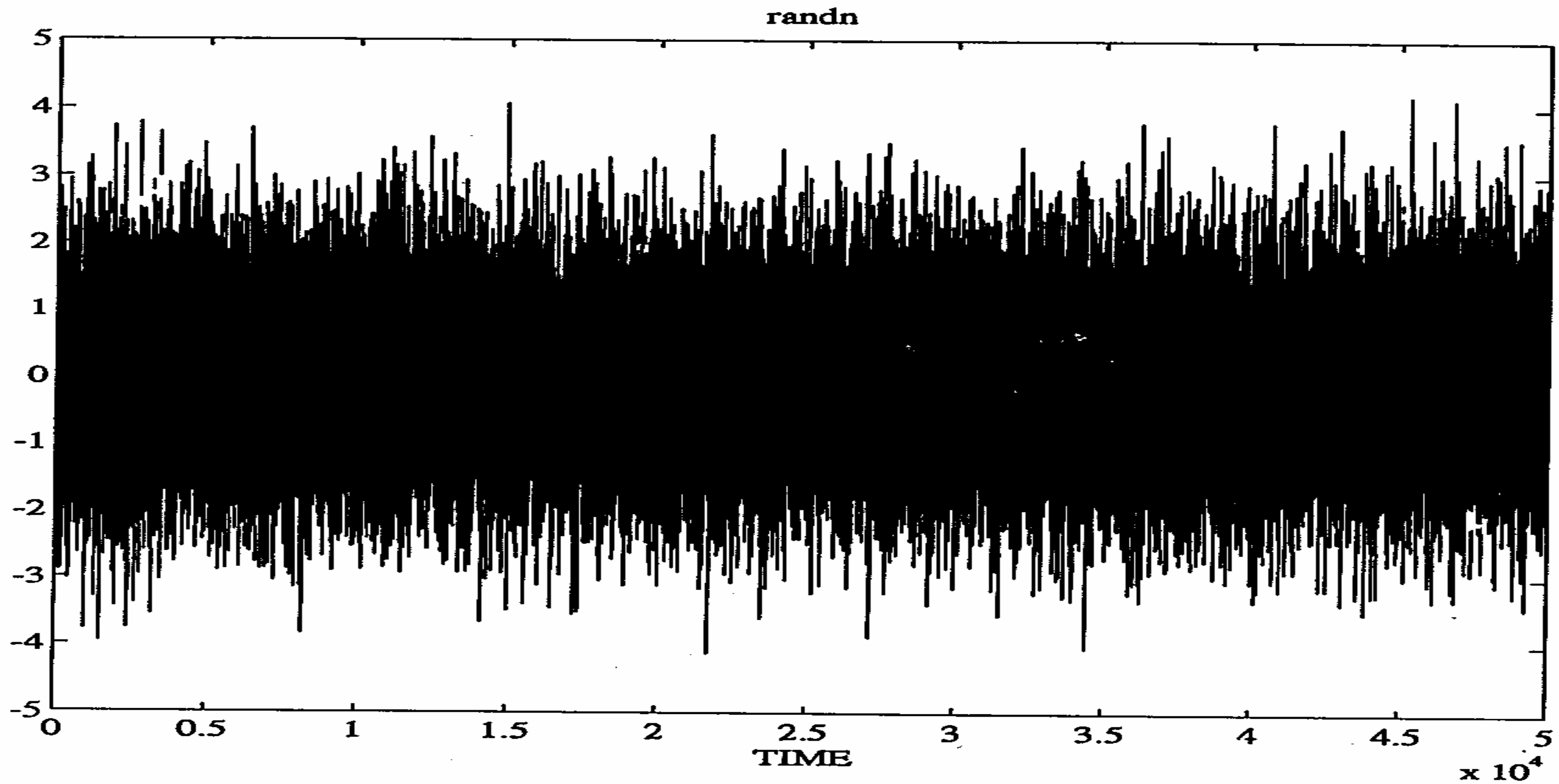
or,

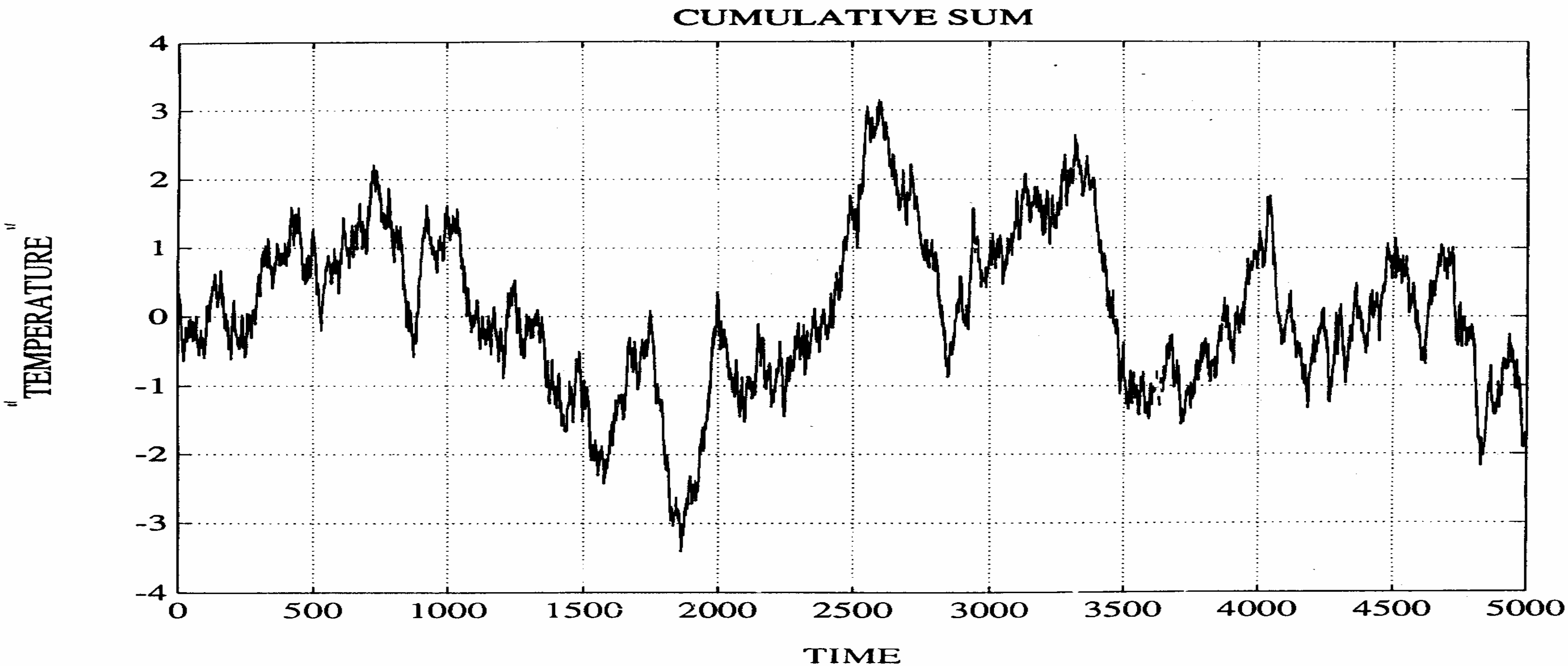
$$T(n\Delta t + \Delta t) = T(n\Delta t) + \Delta t q(n\Delta t)$$

and let us determine $q(n\Delta t)$ from a table of random numbers.

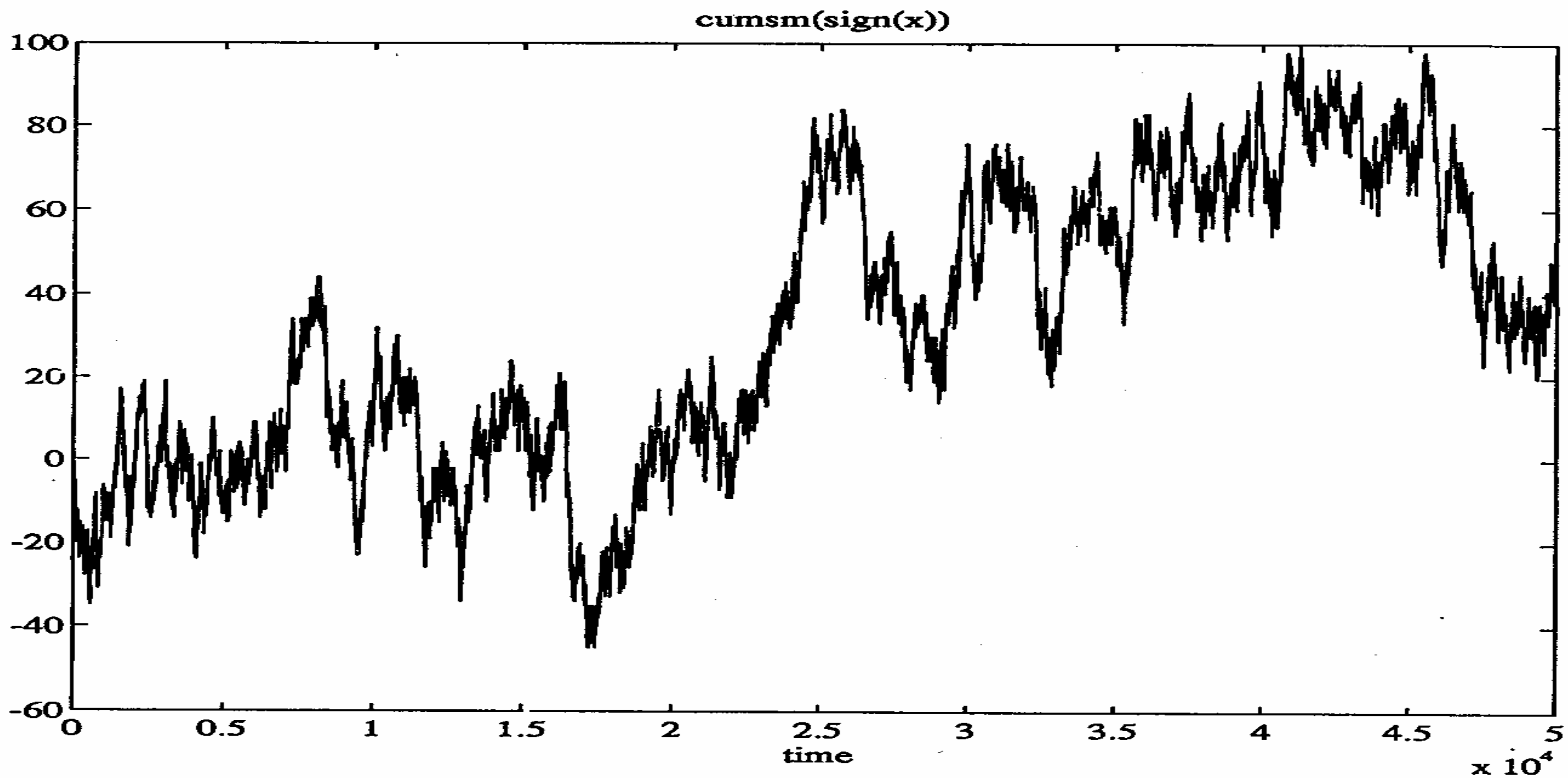
In probability theory, the problem of determining the value of T(t) is known as the “game of Peter and Paul” in which q is decided by the flip of a coin. Has some bizarre properties.

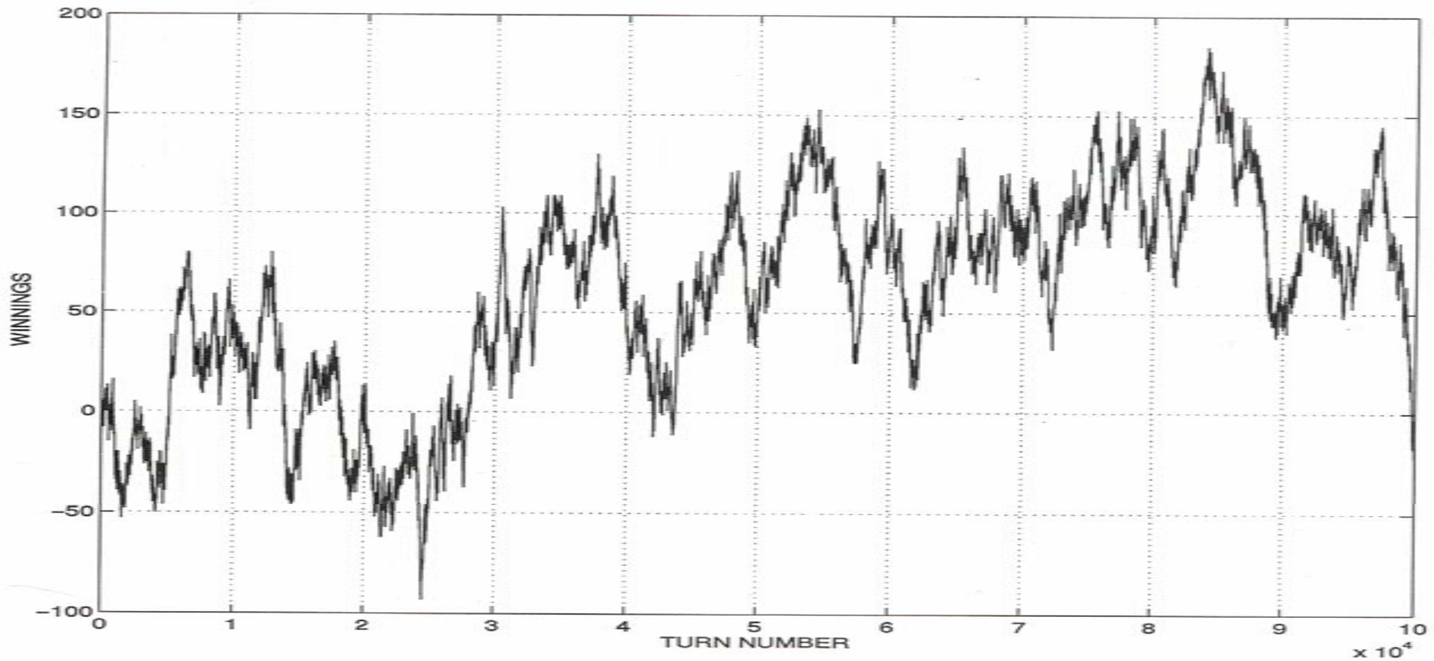



randn
5
4
3
2
1
0
-1
-2
-3
-4
-5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
TIME
x 10^4



CUMULATIVE SUM
4
3
2
1
0
-1
-2
-3
-4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
TIME
"TEMPERATURE"


cumsm(sign(x))
100
80
60
40
20
0
-20
-40
-60
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
time
x 10^4


200
150
100
50
0
-50
-100
WINNINGS
0
1
2
3
4
5
6
7
8
9
10
TURN NUMBER
x 10^4

More generally, many geophysical processes are described as "colored noise" and representable as so-called autoregressive models:

$$y(n) = a_1 y(n-1) + a_2 y(n-2) + \ldots + a_N y(n-N) + \theta(n)$$

where $\Delta t = 1$ by definition and $\theta(n)$ is completely random (called "white noise").

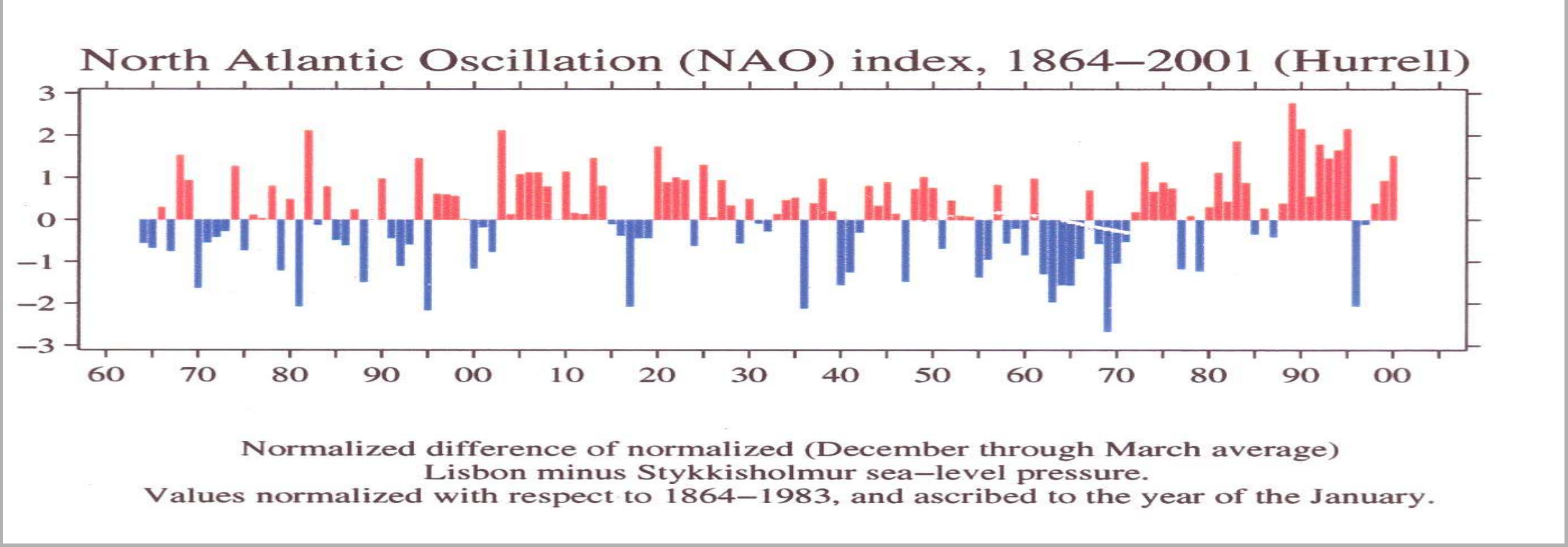
An equivalent model is a so-called moving average:

$$y(n) = b_1 \theta(n) + b_2 \theta(n-1) + \ldots + b_M \theta(n-M)$$

Such random models give rise to time series with lots of interesting structure, about which one must again develop an intuition.

A lot of the difficulty concerns the visual resemblance of time series that are truly unrelated:

Note the “trend” toward the end



Such time series can give rise to apparent trends, oscillations and other highly misleading features:

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When have two or more time series, must be very wary of inferring by eye that they are related.

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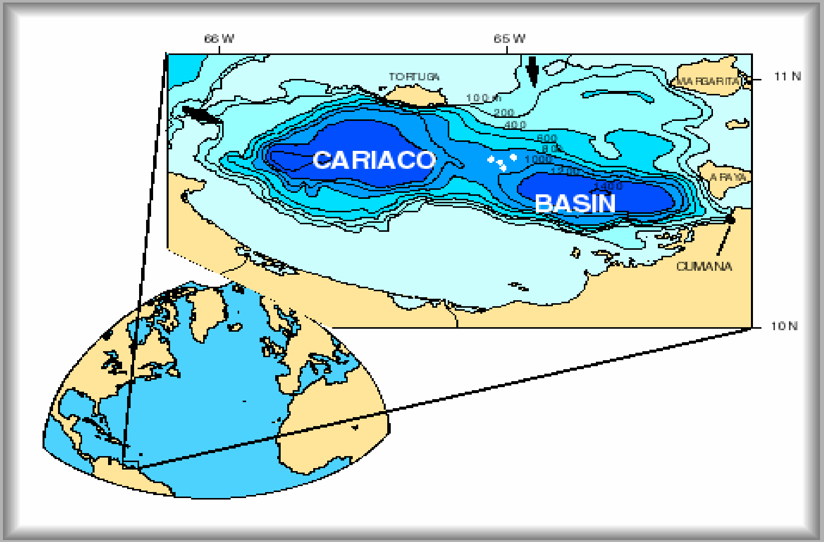


Cariaco Basin reflectance & GISP2 ice core
Peterson et al., 2000, Science.

Supposed to show that the Dansgaard-Oeschger events appear at low latitudes as well as in Greenland.

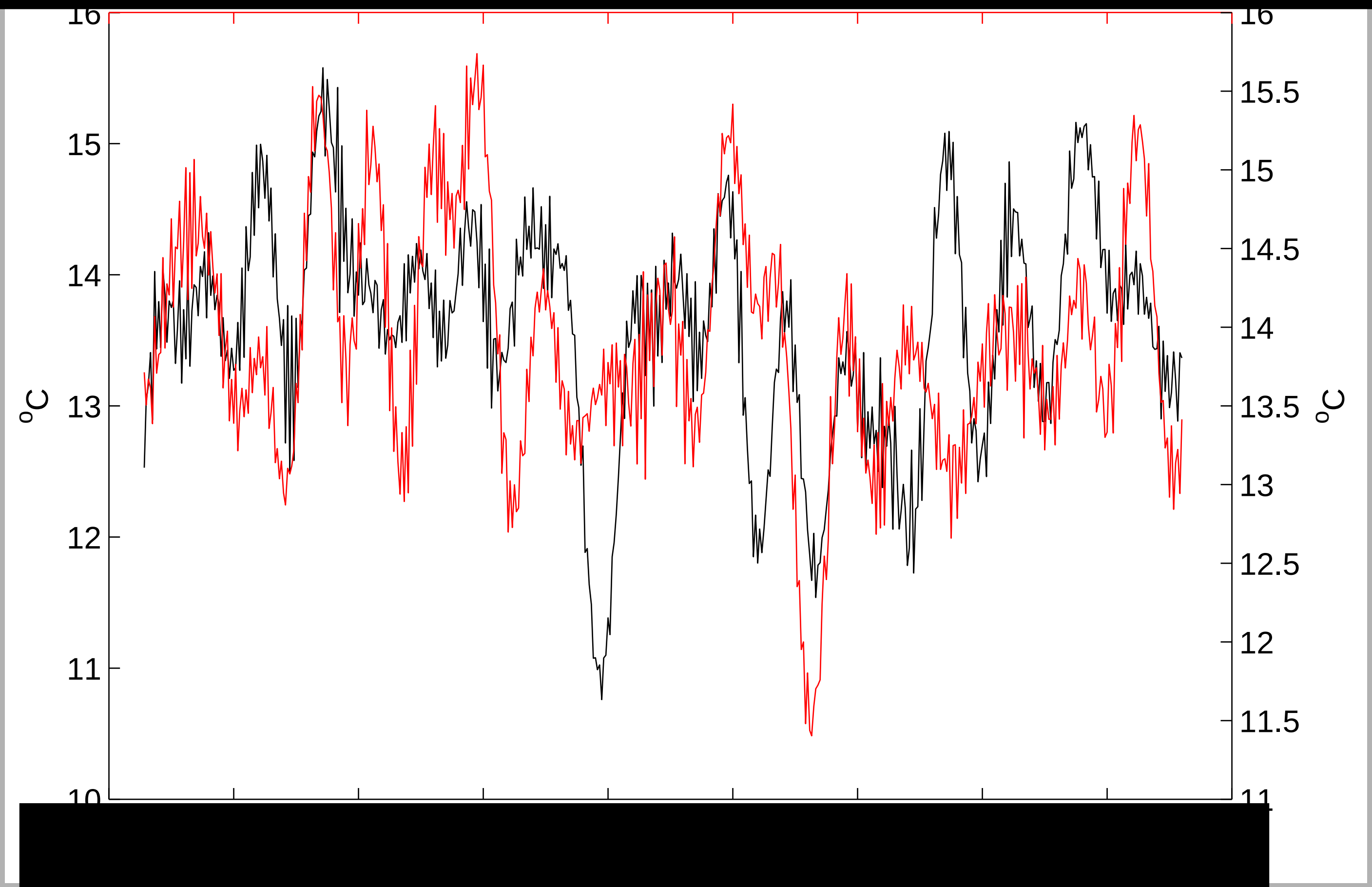
Image removed due to copyright restrictions.

Hulu Cave (eastern China)/GISP2
R. Alley, Oceanography, 2005

Images removed due to copyright restrictions.

Santa Barbara Basin/GISP2,
Hendy, Kennett, Roark, Ingram, QSR, 2002

[redacted]



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Two real records

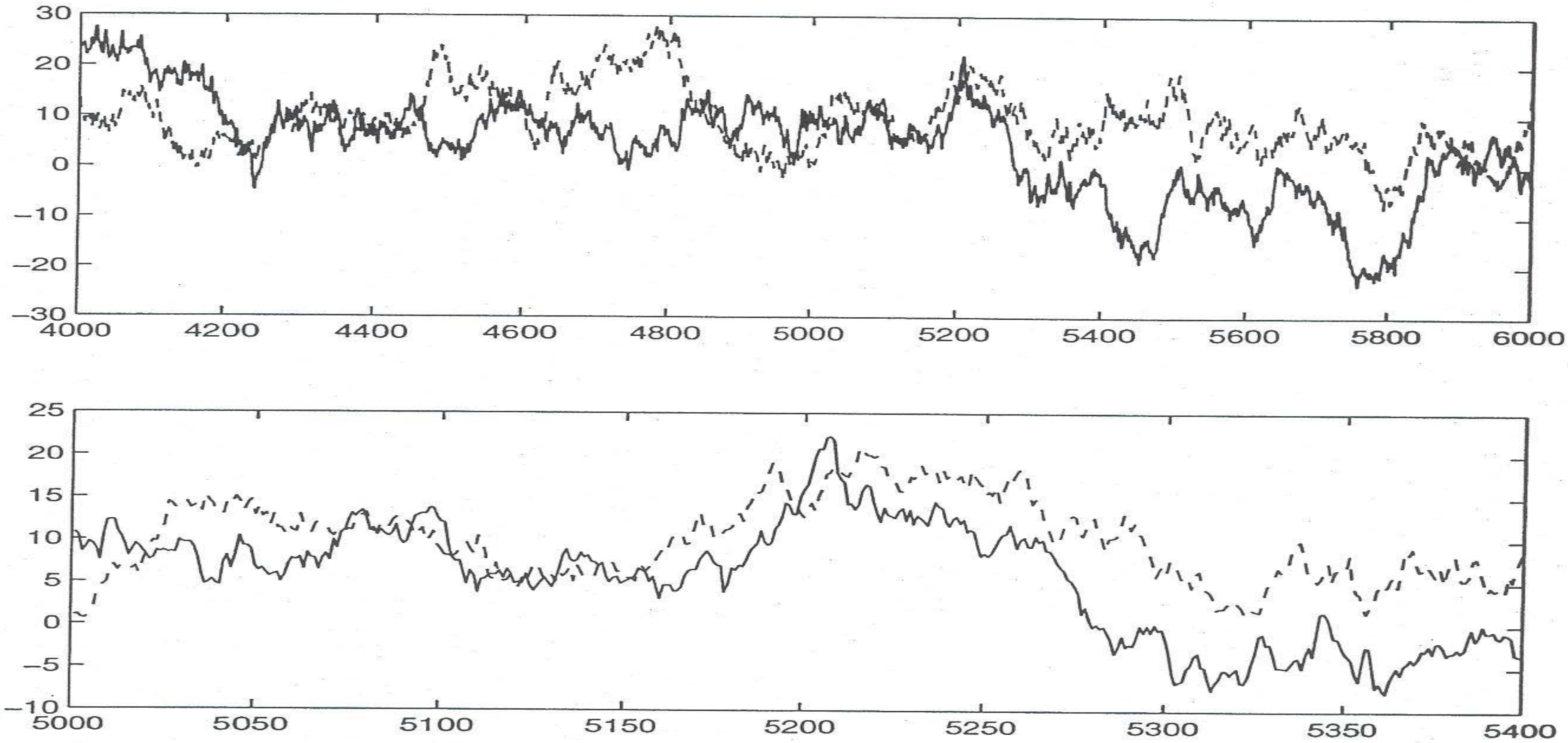
rate of crossing of the mean: $\left(1/2\pi\sqrt{\lambda_2/\lambda_0}\right)$

$$\lambda_k = \int_{-\infty}^{\infty} |\omega|^k \Phi(\omega)\, d\omega, \quad k = 0, 1, 2, \ldots,$$

The issue is that two completely unrelated time series, having similar frequency content (spectral shape) necessarily display on average the same numbers of maxima and minima in any given time interval.

There are statistical tests available that prevent one from inferring spurious similarity that is only an accident. (Sometimes known as the Slutsky-Yule effect.)

expanded AR(1)   21–Feb–1998 10:39:08 CW



Chaotic behavior can be equally misleading if one examines records that are too short in duration:

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The transport in the Gulf Stream---deterministic? or random?

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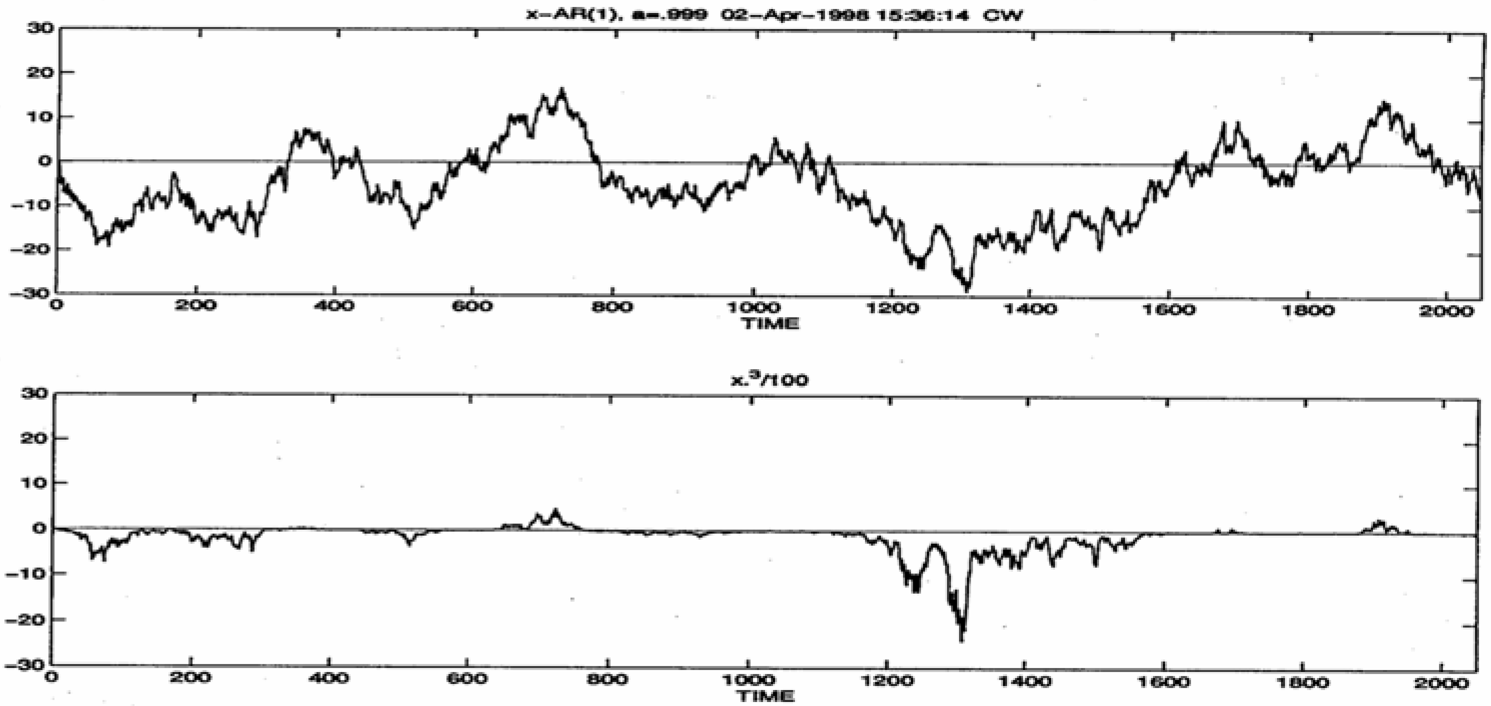
Note that “deterministic” chaos and stochastic behavior can be extremely difficult to distinguish.



Non-stationary or non-Gaussian? Stationary means that the statistics remain constant through time.

(The top curve is stationary (by construction). The bottom curve is just the cube of the top one---it looks non-stationary but is actually completely stationary---it just isn't Gaussian).

From a paper claiming that deglaciations occur every four or five precession cycles. If look at it carefully, discover that the match is no better than chance. (Huybers and Wunsch 2005, Nature)

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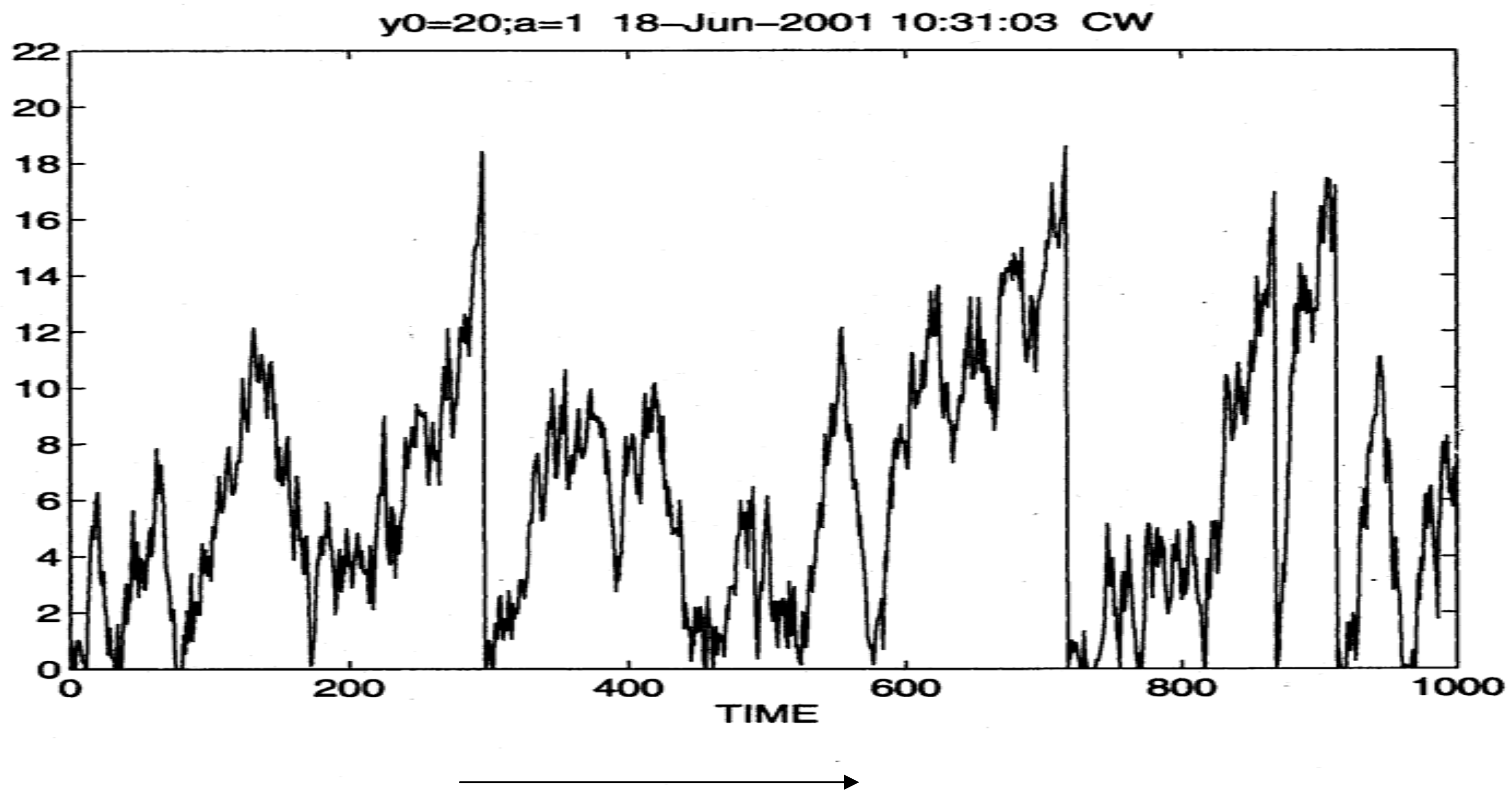
Milankovitch Hypotheses

"It is widely accepted that climate variability on time scales of 10^3 to 10^5 years is driven primarily by orbital, or so-called Milankovitch, forcing." (McDermott et al., *Science,* 2001).

"...it is now quite clear that orbital forcing played a key role in pacing glaciations during the Quaternary...." (Bradley, R. S., *Paleoclimatology,* Academic Press, 1999, p. 281)

"The orbital theory of climate is the prevailing theory of glacial-interglacial climate change over tens of thousands to hundreds of thousands of years." (Cronin, T. M., *Principles of Paleoclimatology,* Columbia Un. Press, 1999, p. 131)

"Many phenomena in the physical sciences lend themselves to the conjecture that there exists some underlying structure or periodicity in different kinds of data. The development of unbiased tests becomes critical... Astronomy, especially, has had a long history of claim of pattern and form which ultimately proved false. Sheehan (1988), a psychiatrist and psychologist, has considered the evolution of planetary astronomy and how observational information of a largely qualitative sort became subject to misinterpretation, a consequence of the way the eye and brain function together. The observational claims by Schiaparelli and Lowell of 'canals' on Mars is a classic case of this phenomenon. Only recently have psychologists developed an appreciation for how the eye seemingly finds pattern where none exists. ...researchers such as Julesz (1981) have succeeded in *quantifying* how images...could suggest to viewers the presence of pattern that ...statistical methods then showed to be nonexistent." W. I. Newman, M. P. Haynes and Y. Terzian, Redshift data and statistical inference, Astrophysical J., 431, 147-155, 1994.



It is possible to make purely random time series that produce a dominant time scale. (Wunsch, 2003, Climate Dynamics).