# Climate Dynamics

Determinism vs. Chaos Theory

Perturbation

Positive Feedback (amplifies a perturbation)

Negative Feedback (opposes a perturbation)

Stability of the climate system:

Stable, Neutral, or Unstable

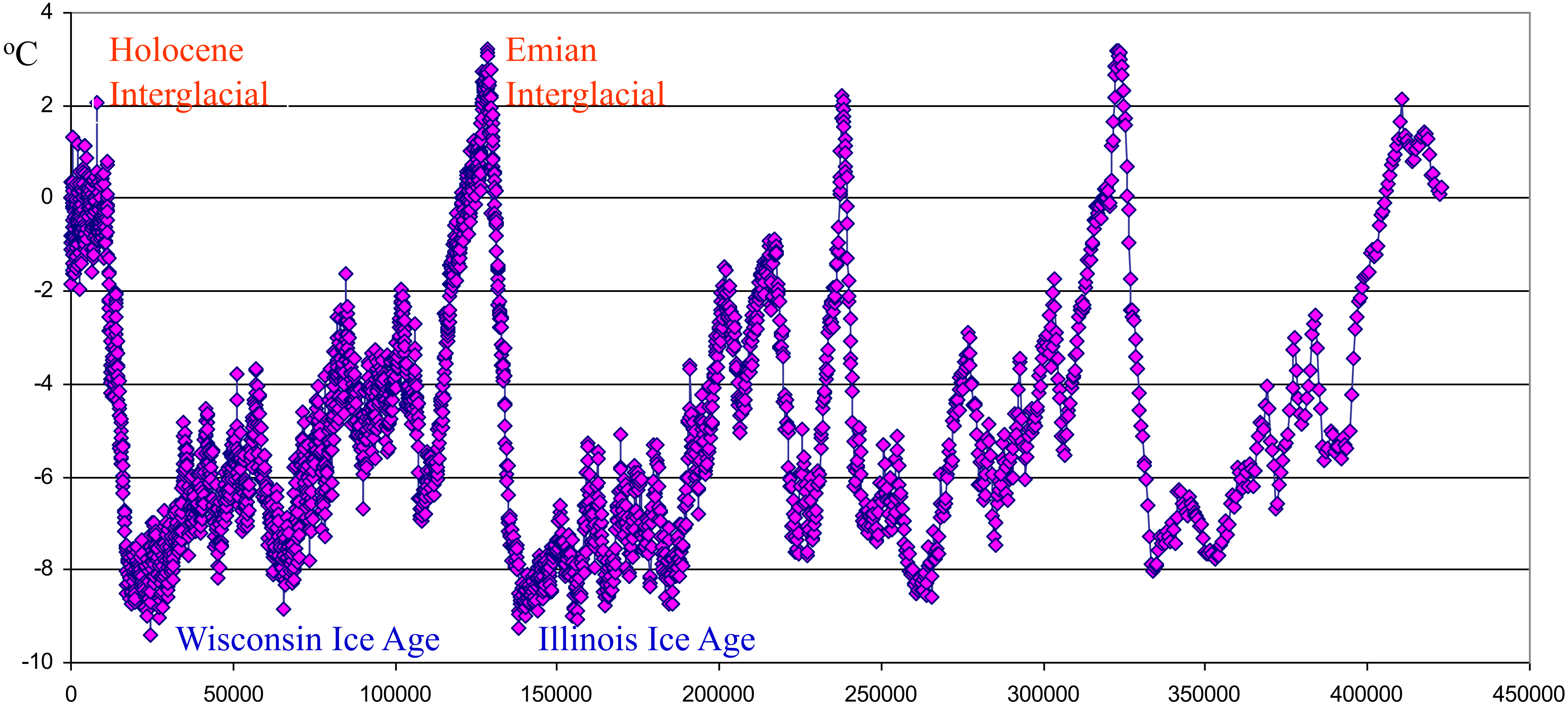


Figure 4.2. Global temperature variations over the last four glacial / interglacial cycles inferred from Vostok deuterium [Petit et al. 2001; data from www.ncdc.noaa.gov/paleo].

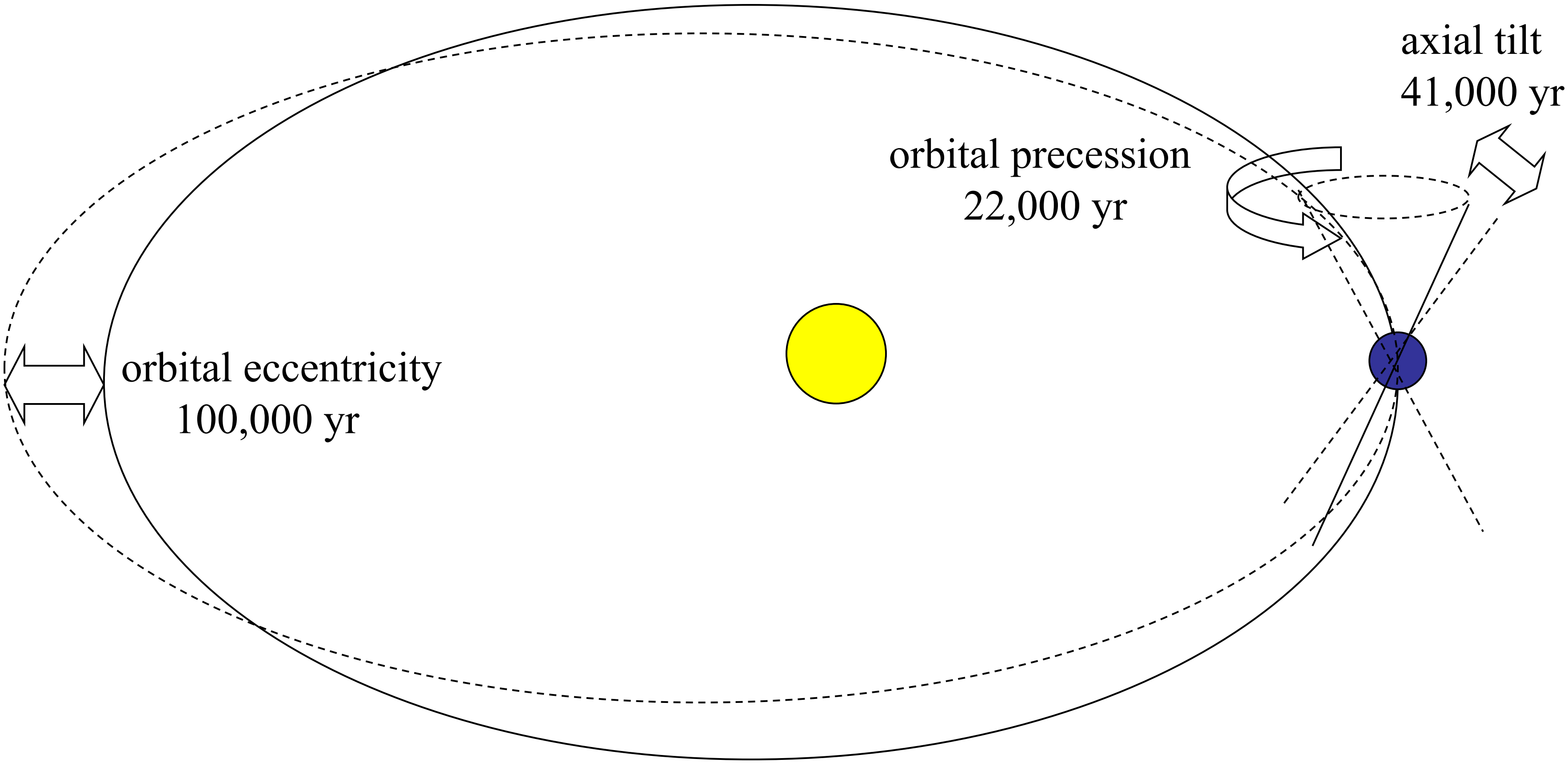


Figure 4.16. Variation in earth orbital parameters as the basis for the Milankovich theory of glacial / interglacial cycles.

Milutin Milankovich 1930 (celestial mechanics; cf. Copernicus, Croll)

Eccentricity – varies from 0.0034 to 0.058 and back every 100,000 years

Solar intensity varies by 3-20% around the orbit

Current value 0.0167 and 7% solar intensity variation

Axial Tilt – varies from 22° to 24.5° and back every 41,000 years

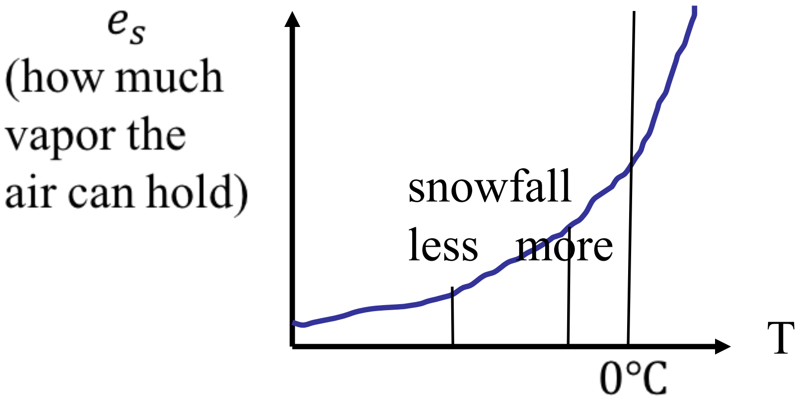
Weak axial tilt (weak seasons) favors snow accumulation

Axial Precession – pointing direction goes in a circle every 22,000 years

NH summer when close to sun favors melting and strong monsoons

At one meter per year, it would take 5000 years to build up 5000 m of ice

Why does a warmer winter favor snow accumulation?



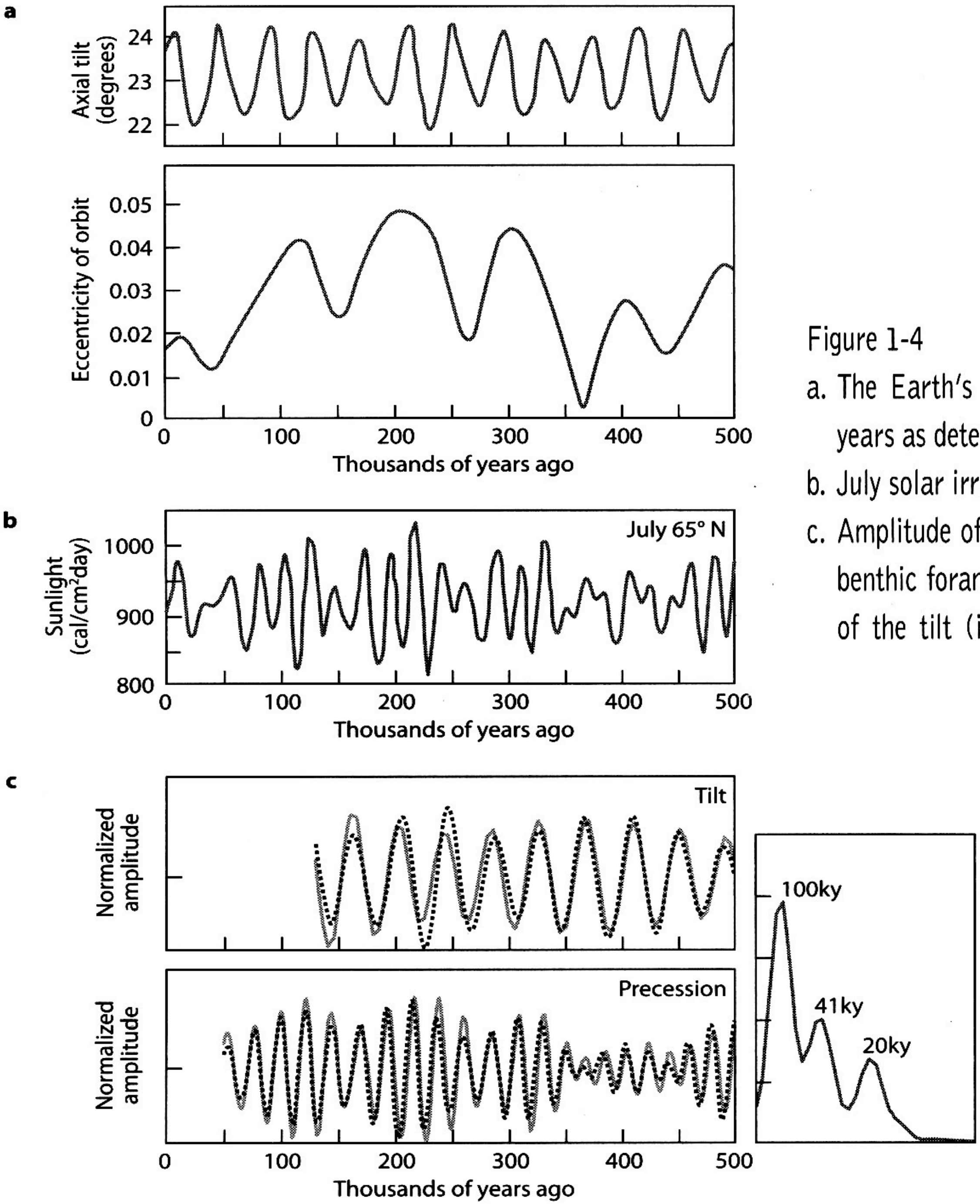


Figure 1-4

a. The Earth's axial tilt and orbital eccentricity over the past 500,000 years as determined by celestial mechanics.

b. July solar irradiance at 65°N over the past 500,000 years.

c. Amplitude of the 41,000- and 20,000-year spectral components of the benthic foraminifera $^{18}O/^{16}O$ record (dashed curve) compared with that of the tilt (i.e., obliquity) and distance (i.e., eccentricity–precession)

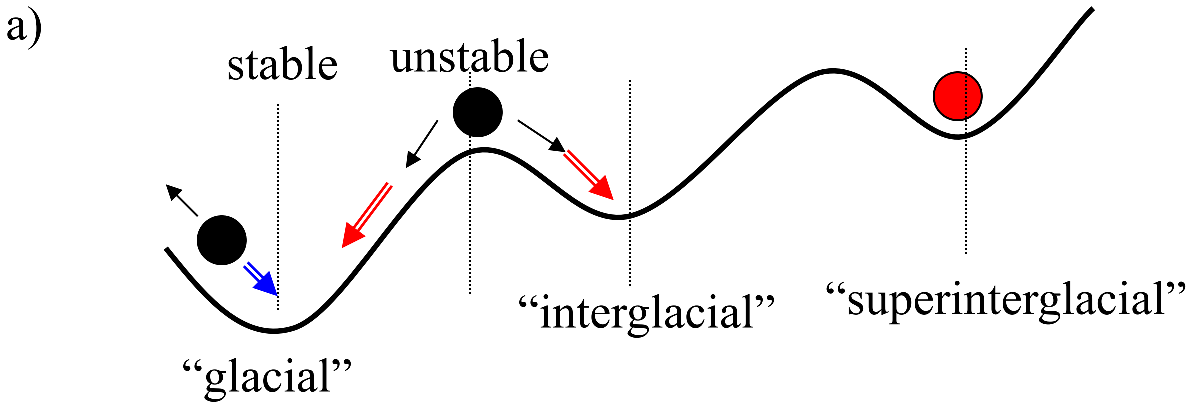
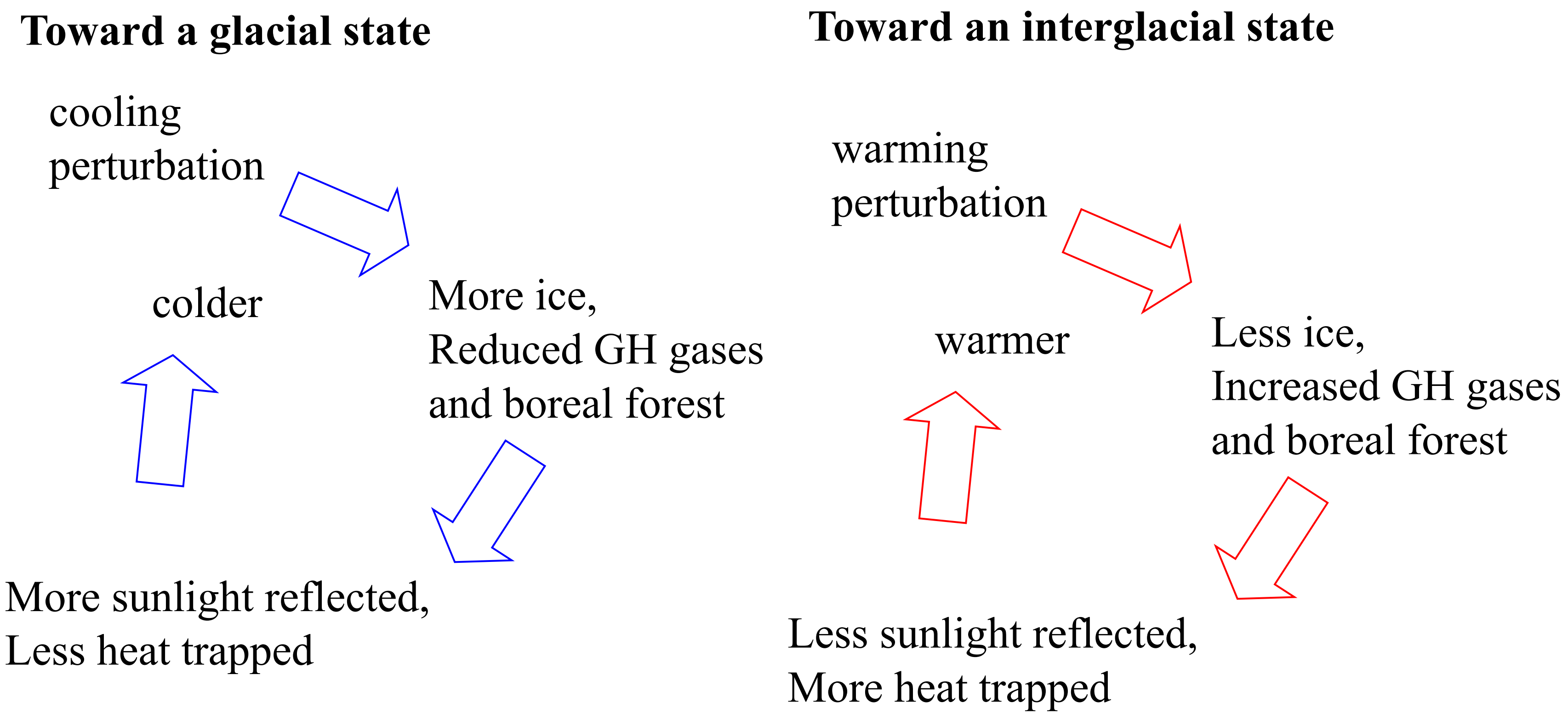


Figure 4.18. a) Idealized "ball bearing" model of the stability of the climate system, showing positive (red arrow) and negative (blue arrow) feedbacks to a perturbation (black arrow). Positive feedbacks amplify a perturbation, destabilizing the system away from equilibrium, while negative feedbacks oppose a perturbation, returning the system to normal, thereby stabilizing the system. Three possible climate states are suggested.



**Toward a glacial state**

cooling
perturbation

More ice,
Reduced GH gases
and boreal forest

More sunlight reflected,
Less heat trapped

colder

**Toward an interglacial state**

warming
perturbation

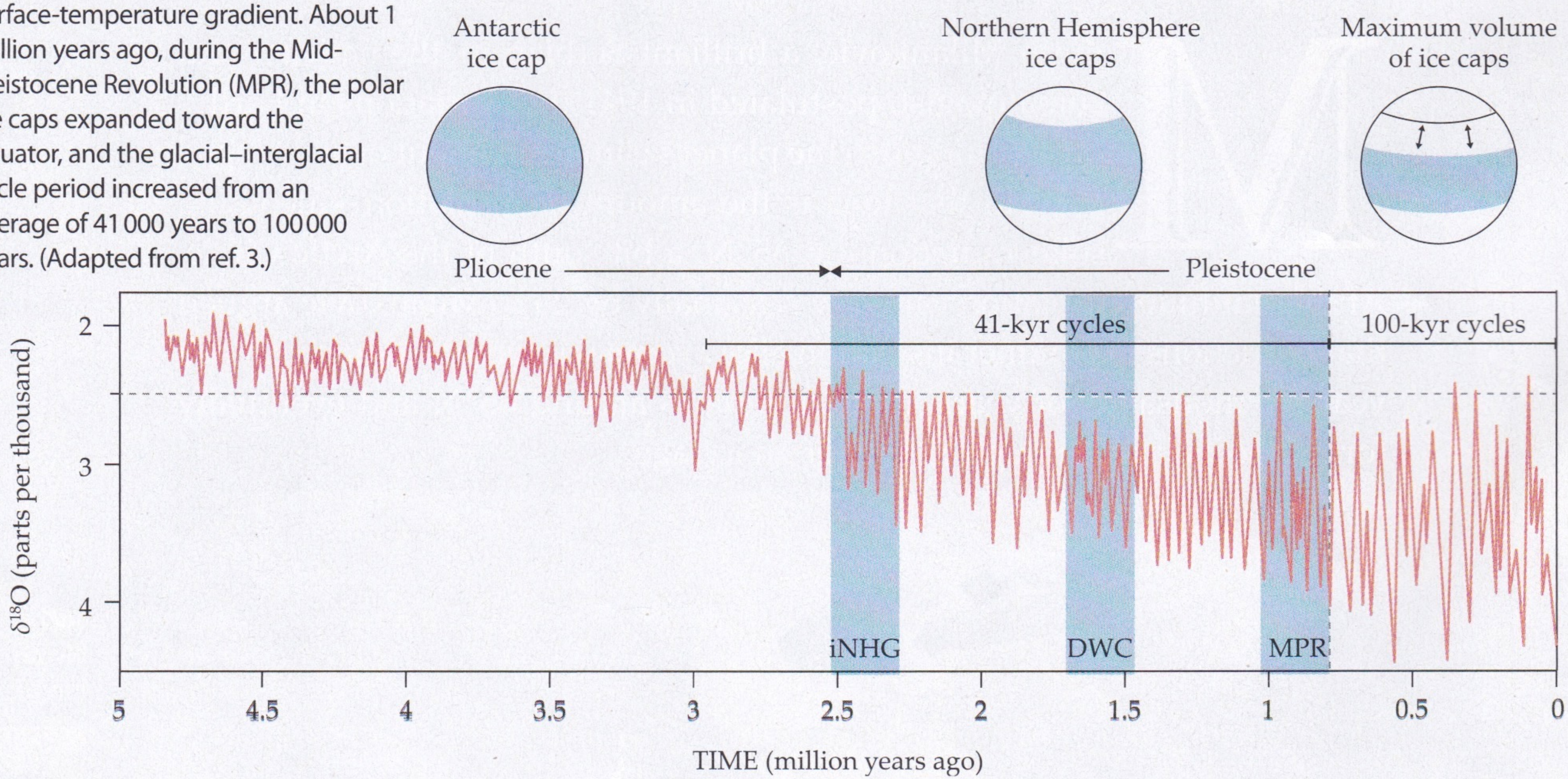
Less ice,
Increased GH gases
and boreal forest

Less sunlight reflected,
More heat trapped

warmer

Figure 4.18b. Positive feedbacks in the climate system help cause it to go into an ice age or into an interglacial, acting to amplify a temperature perturbation of either sign. These include the ice albedo feedback, greenhouse gas feedbacks, and the boreal forest feedback.

**FIGURE 2. MANY GLACIAL–INTERGLACIAL CYCLES** (red solid line) during the last 5 million years can be seen from measurements of the oxygen isotope composition of lake records. Large ice sheets started to grow in North America 2.5 million years ago during the intensification of Northern Hemisphere glaciation (iNHG). The development of the atmospheric Walker Circulation (DWC) started 1.7 million years ago in the Pacific Ocean and is sustained by a large east-to-west sea-surface-temperature gradient. About 1 million years ago, during the Mid-Pleistocene Revolution (MPR), the polar ice caps expanded toward the equator, and the glacial–interglacial cycle period increased from an average of 41 000 years to 100 000 years. (Adapted from ref. 3.)



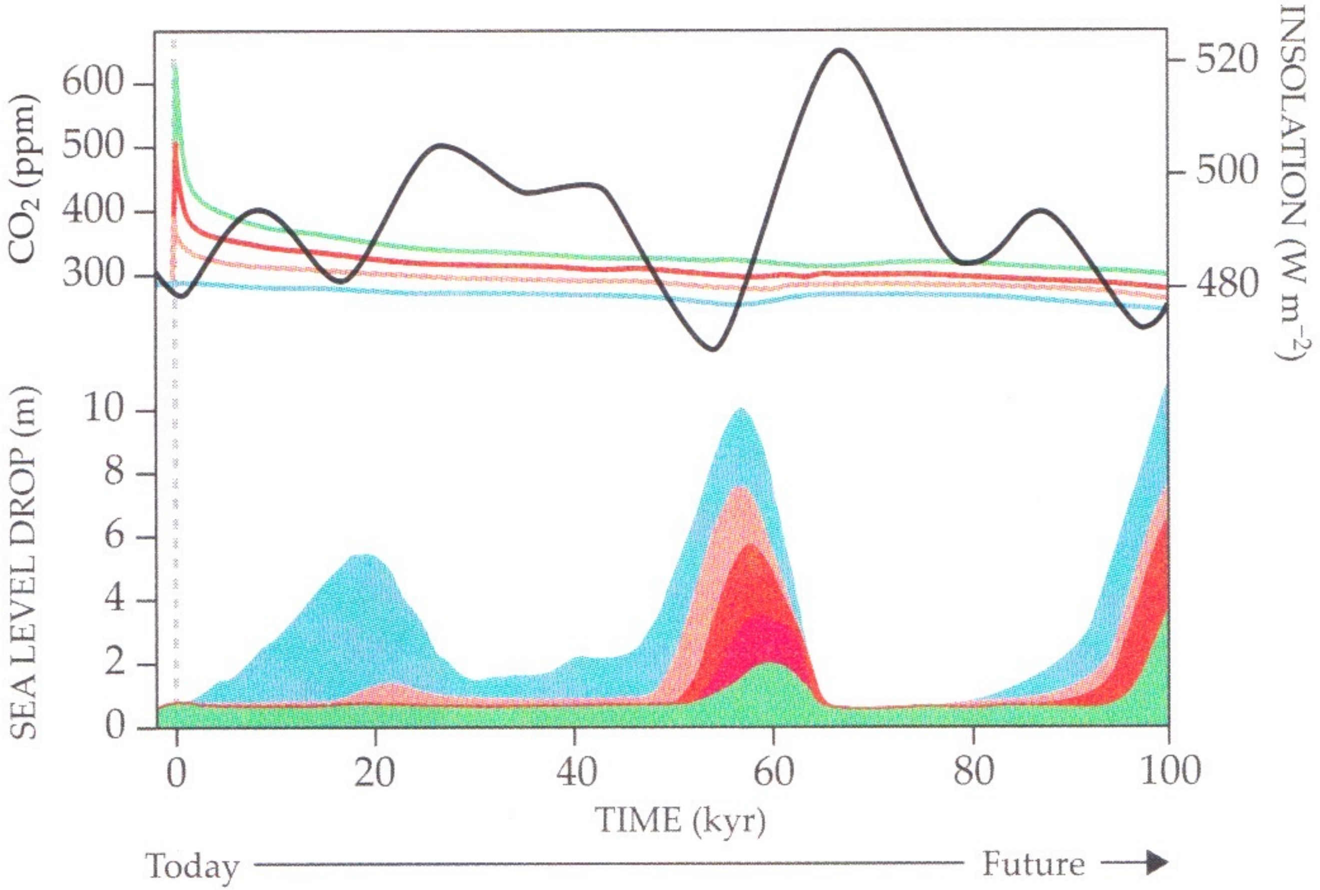
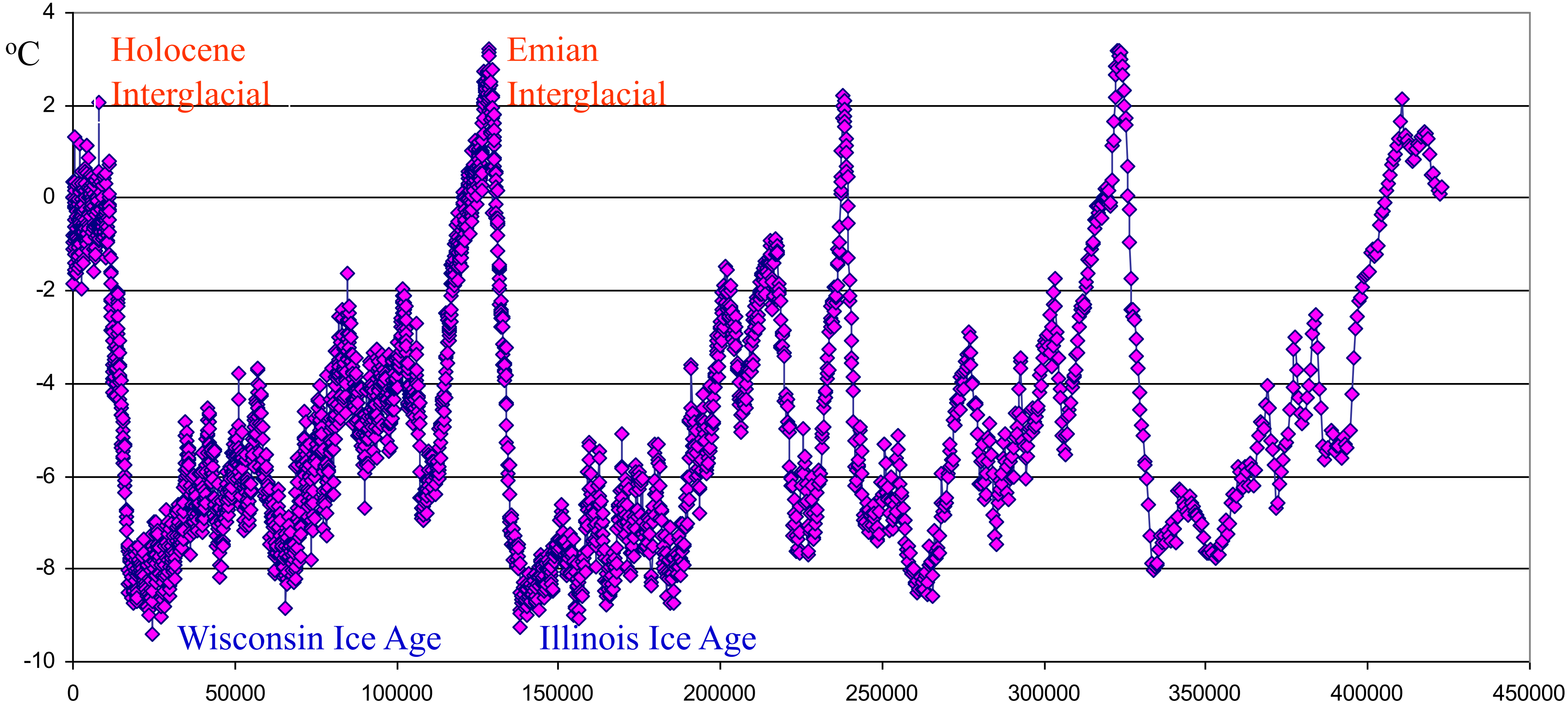


**FIGURE 5. FUTURE ICE AGES** depend on orbital forcing and on the quantity of greenhouse gases humans will emit (colored lines) during the next 100 years. The four corresponding emission scenarios graphed here from climate model simulations—green illustrates the highest emissions, followed by red, orange, and blue—show that anthropogenic climate change dwarfs the effect of orbital forcing and could delay the next ice age for 60 000 years. (Adapted from ref. 15.)



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Chaos Theory

Phase space

Stable attractor

Strange attractor

Unpredictability

Nonlinear interaction in a complex system

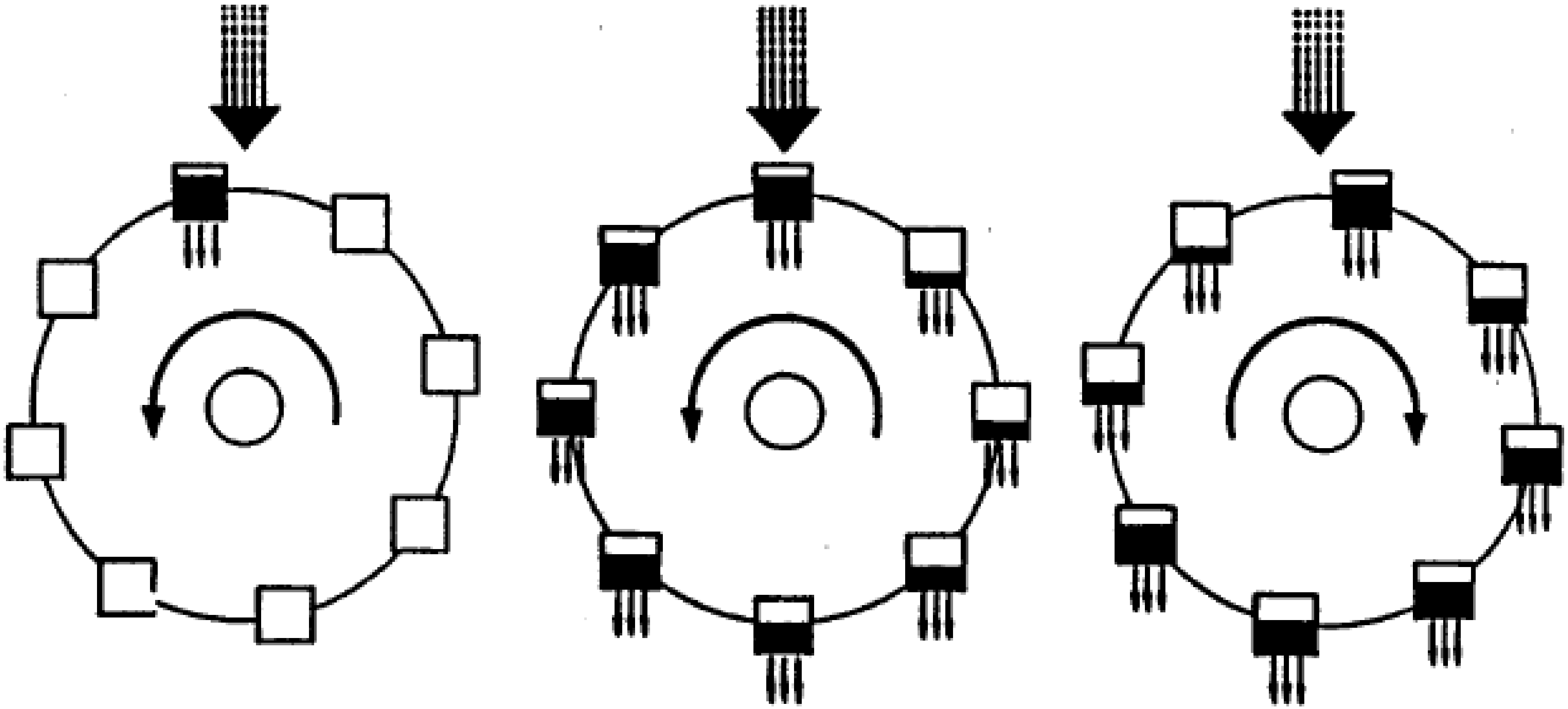
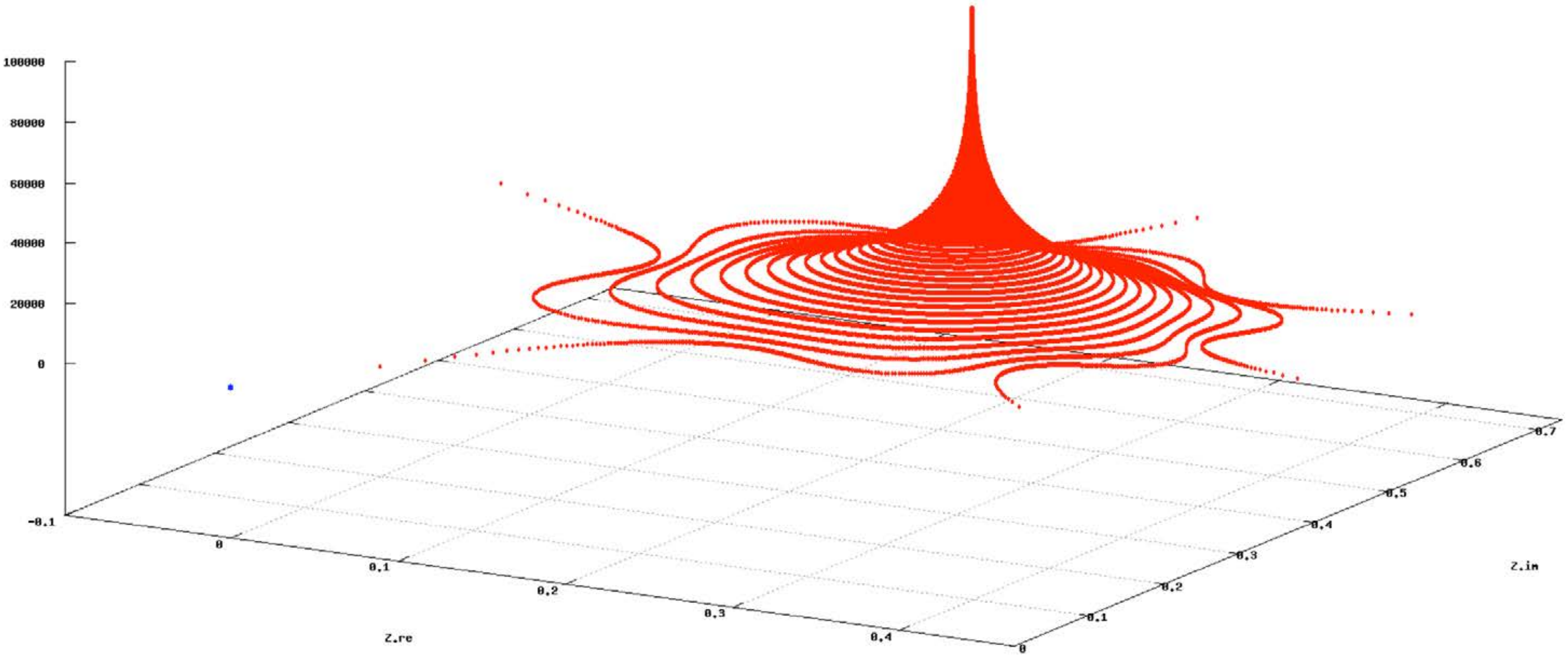


Figure 4.19.

Adolph E. Brotman

**THE LORENZIAN WATERWHEEL.** The first, famous chaotic system discovered by Edward Lorenz corresponds exactly to a mechanical device: a waterwheel. This simple device proves capable of surprisingly complicated behavior.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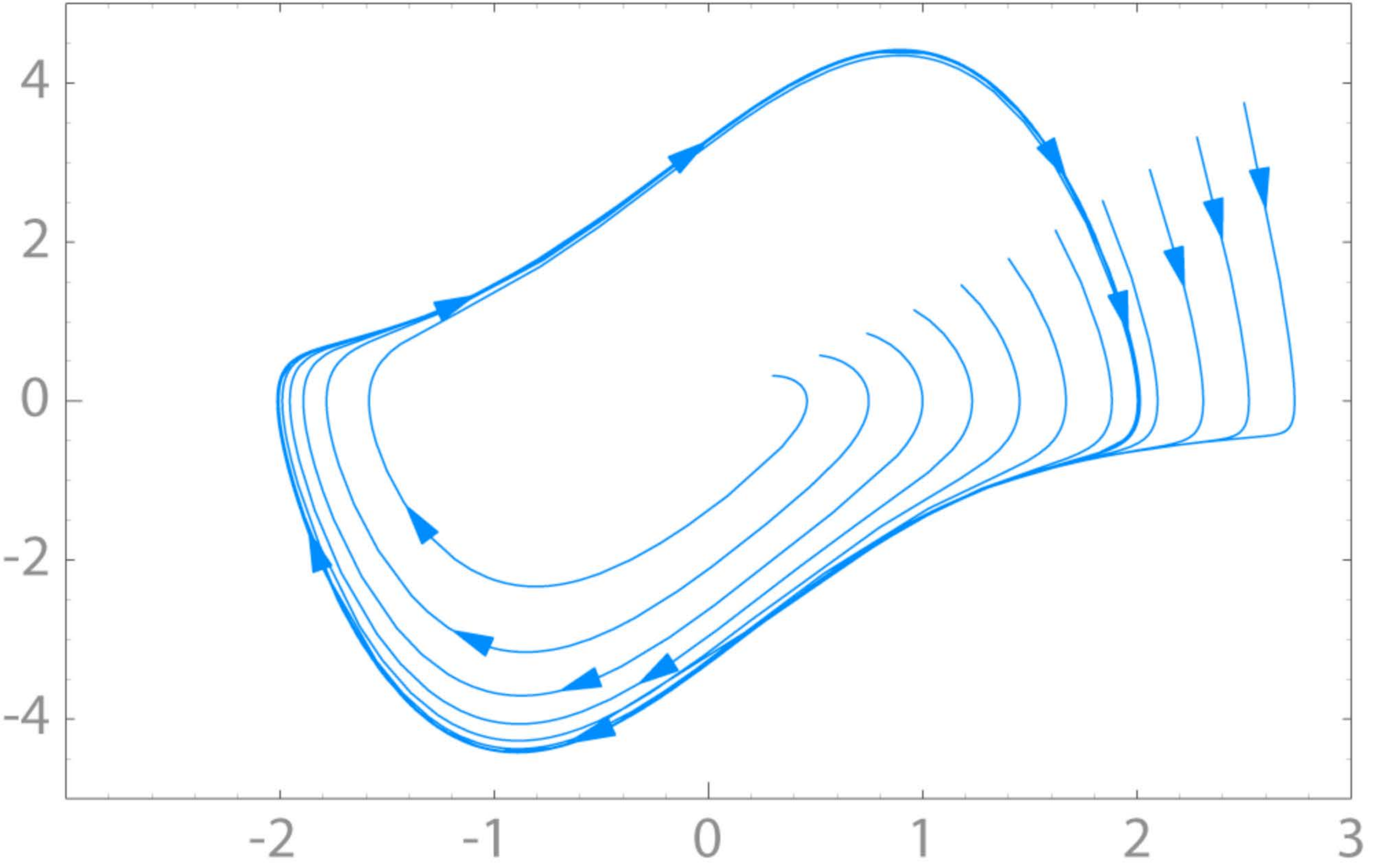
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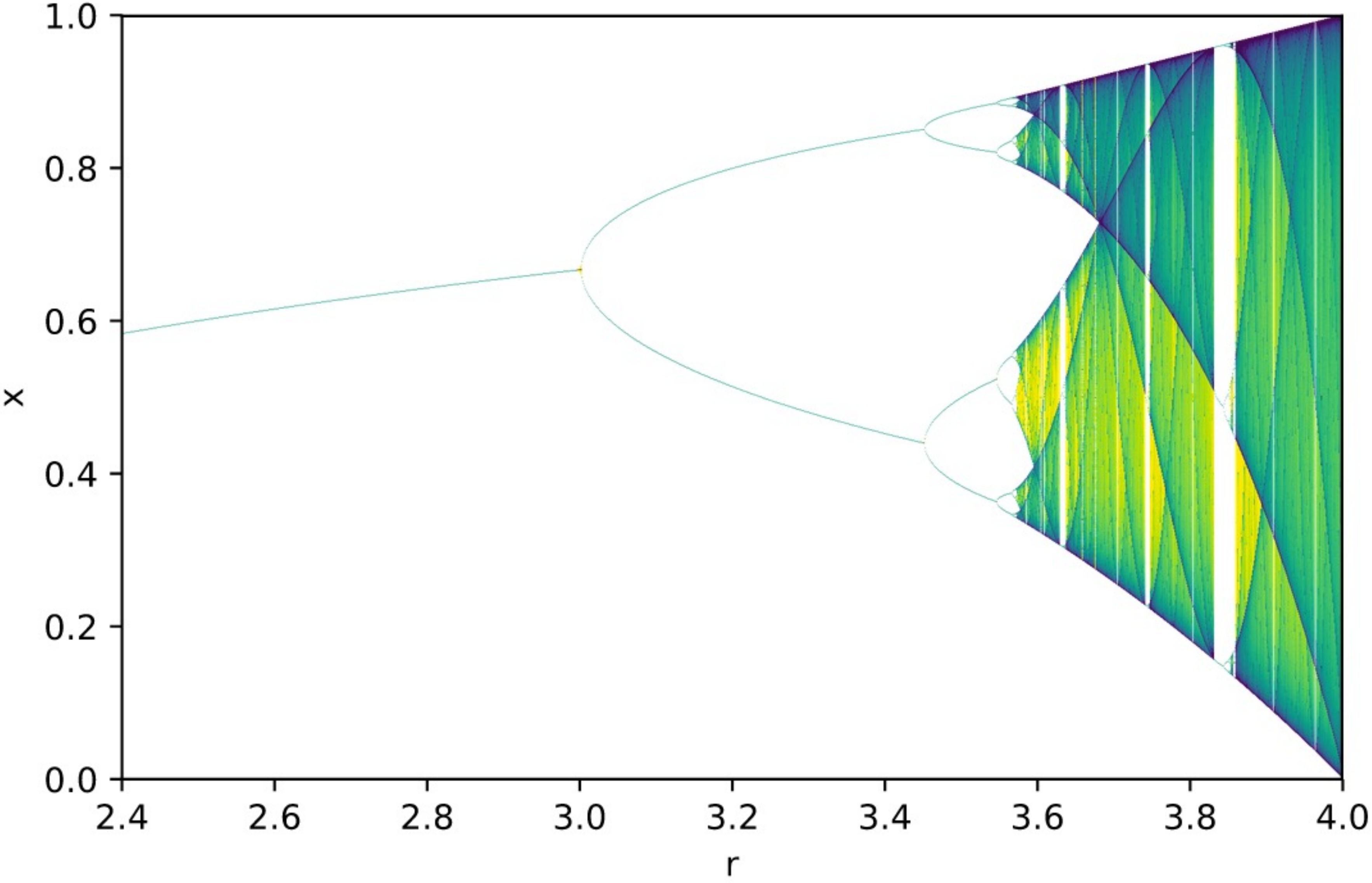
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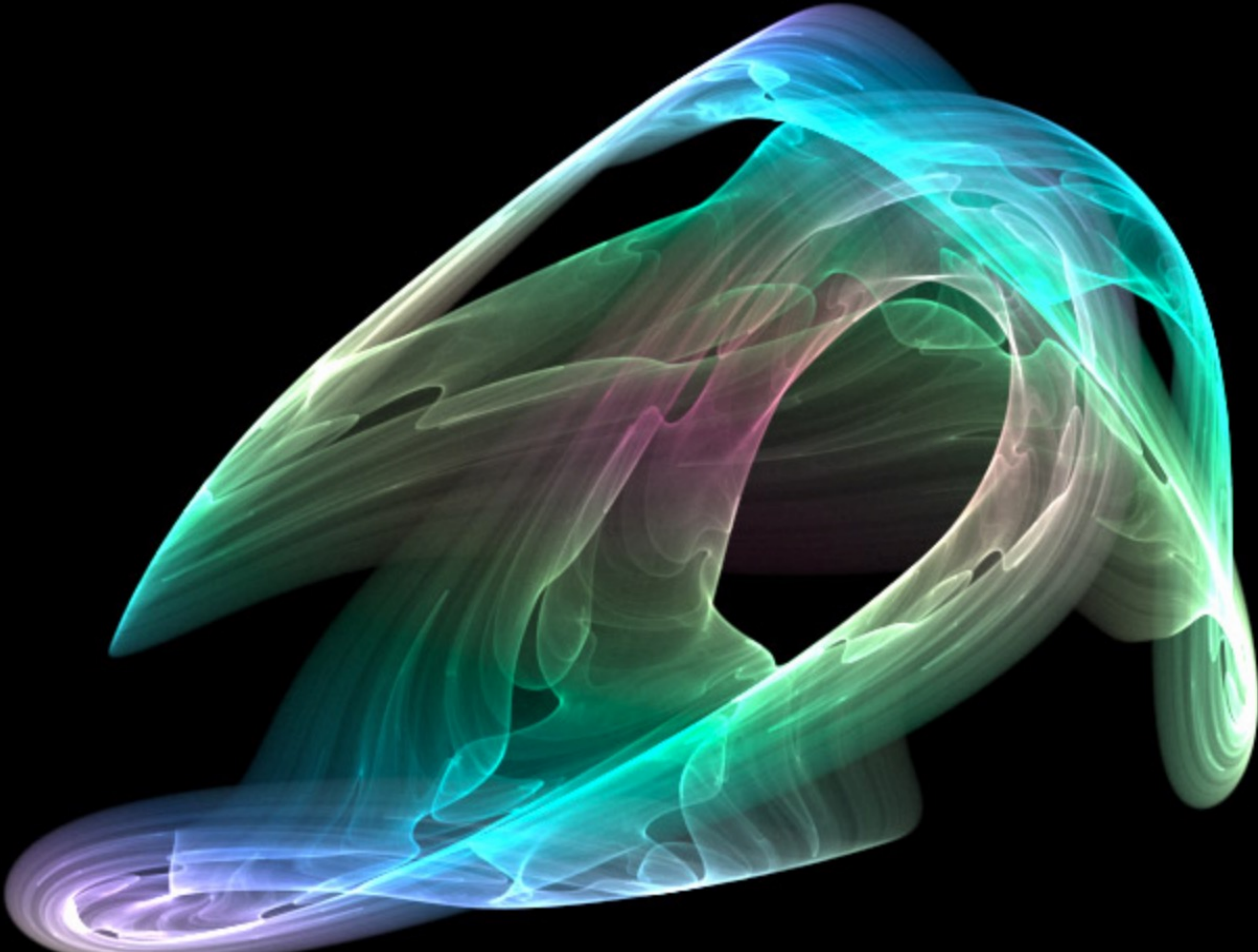

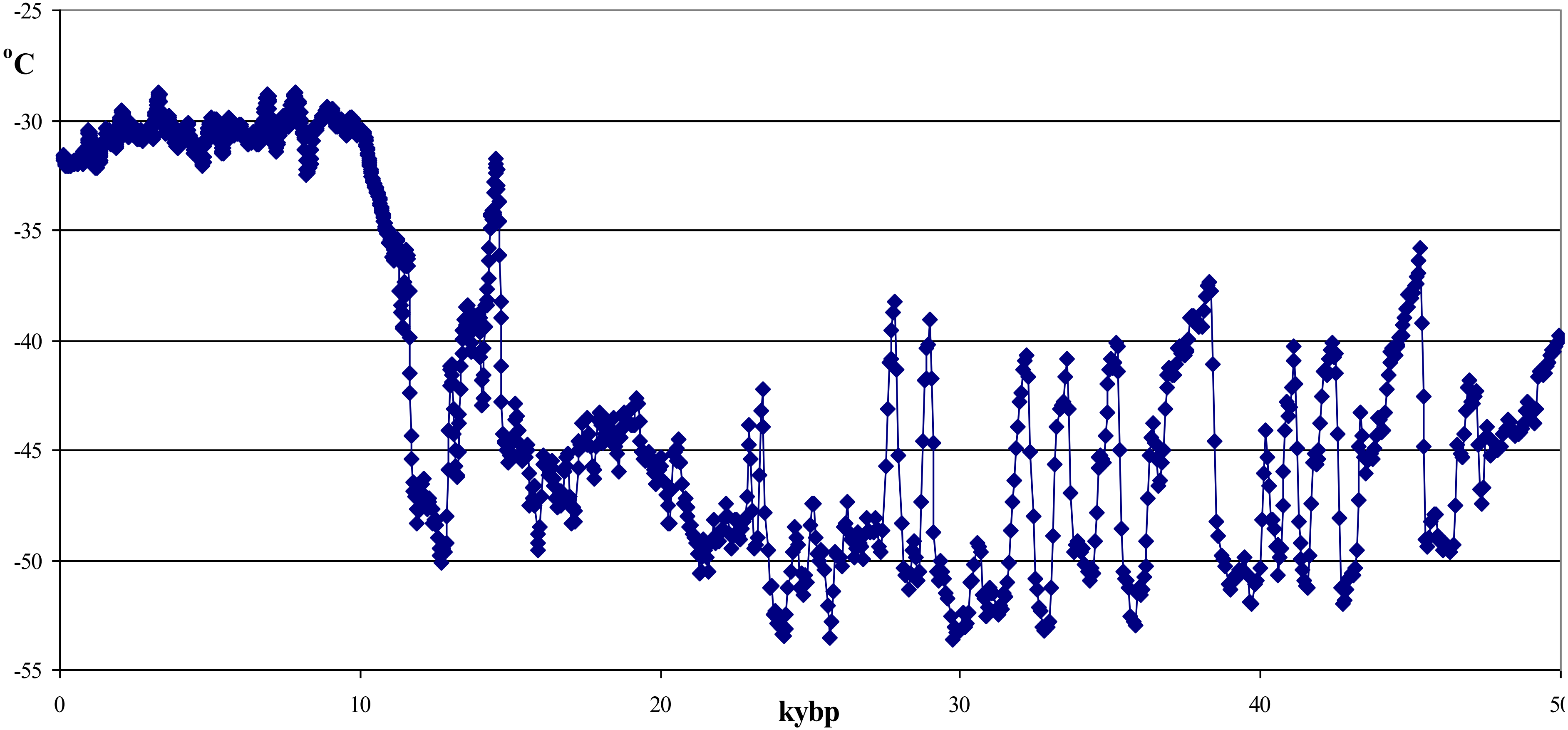

Figure 4.3. Variations in Greenland surface temperature (°C) at GISP2 over the past 50,000 years. Note the common occurrence of Dansgaard-Oeschger events during the Wisconsin Ice Age, but not during the Holocene [Alley et al. 2000, 2004, www.ncdc.noaa.gov/paleo].