

METR 5223: Atmospheric Radiation

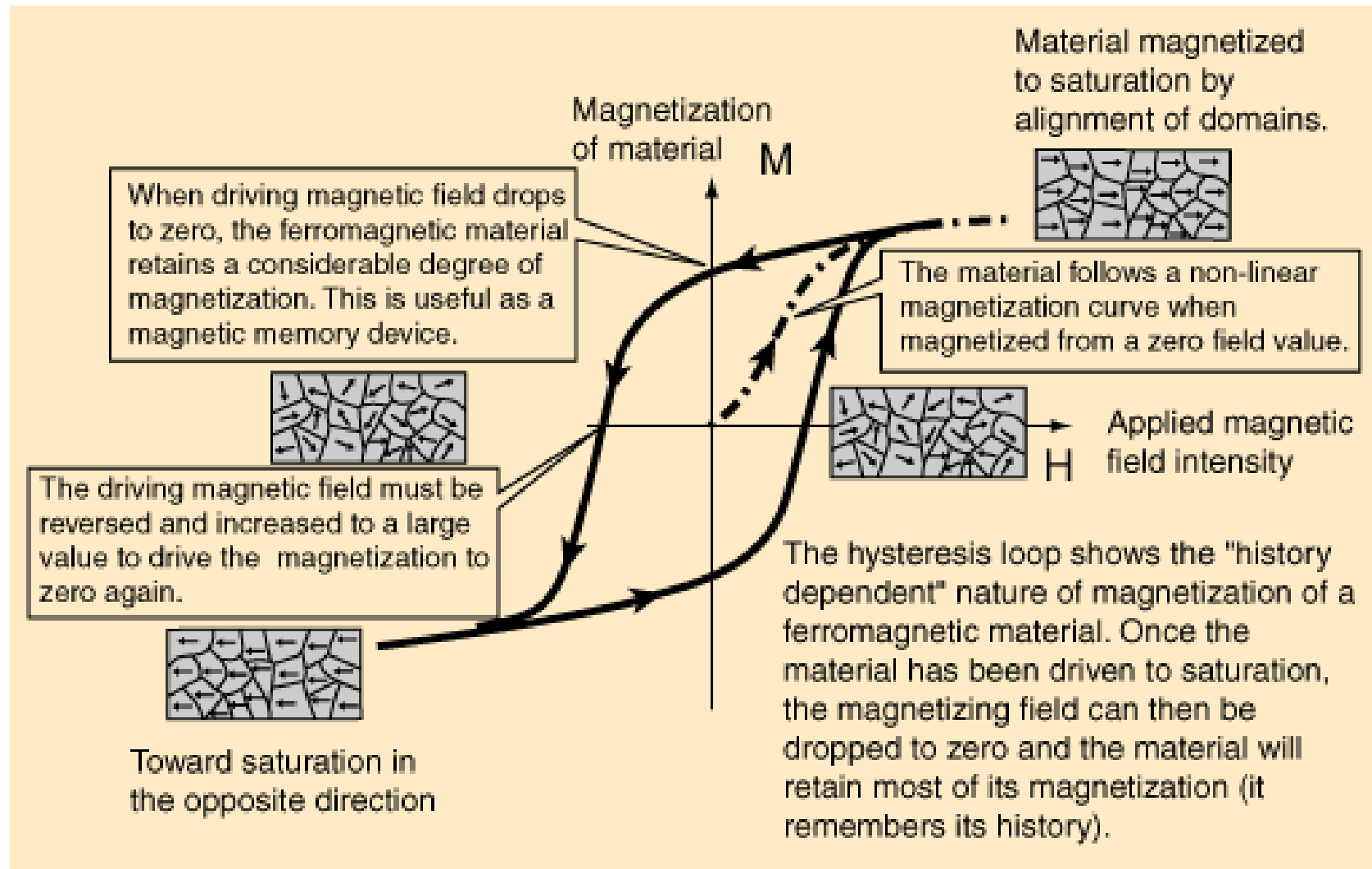
# Multiple Equilibria and Hysteresis

Lecture for Spring 2009

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# Hysteresis (hyperphysics)



A simple climate model, with a hysteresis:

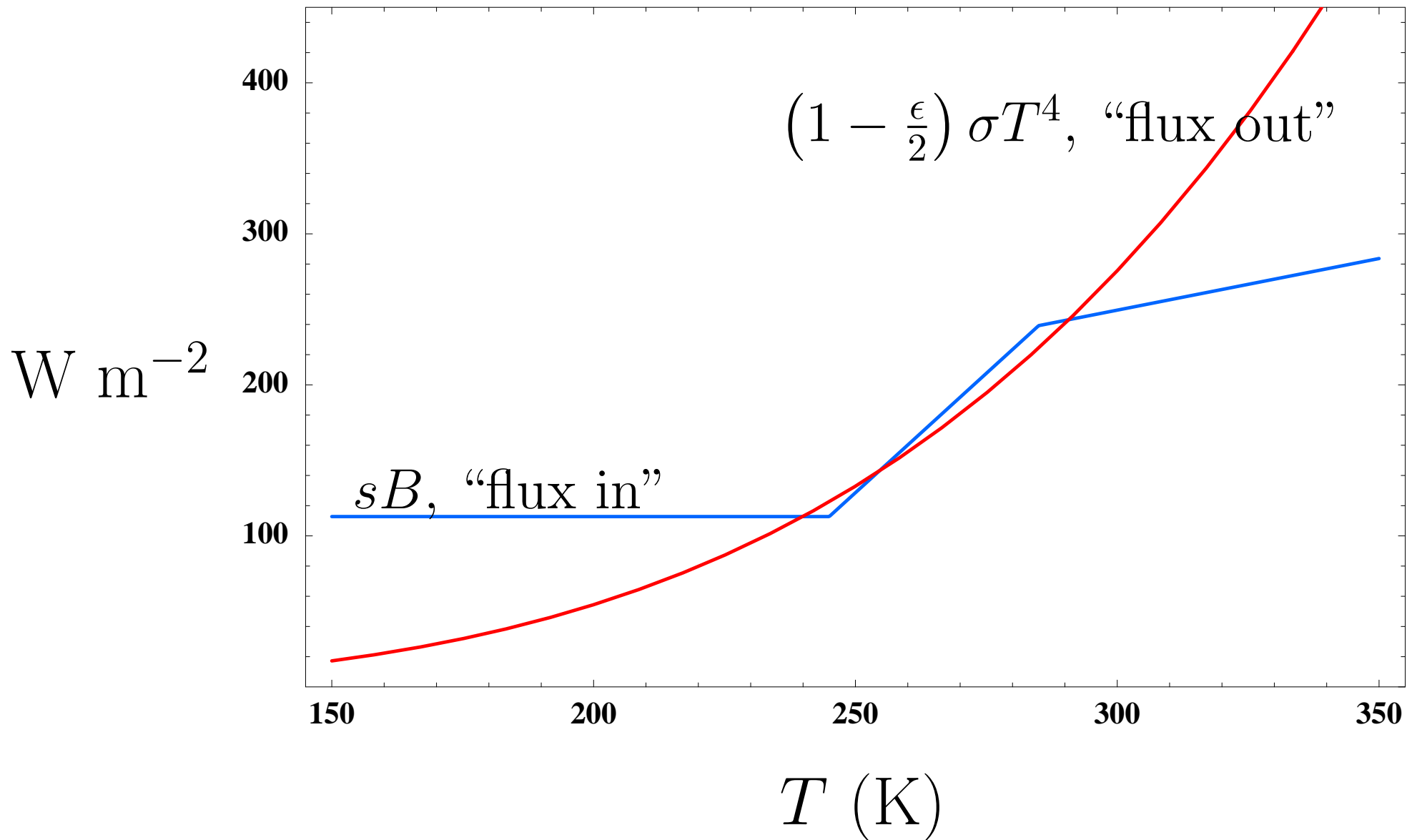
$$C \frac{dT}{dt} = sB - \left(1 - \frac{\epsilon}{2}\right) \sigma T^4$$

$$\epsilon(t) = 0.8 + 0.2 \sin \left( \frac{2\pi t}{100,000 \text{ yr}} \right)$$

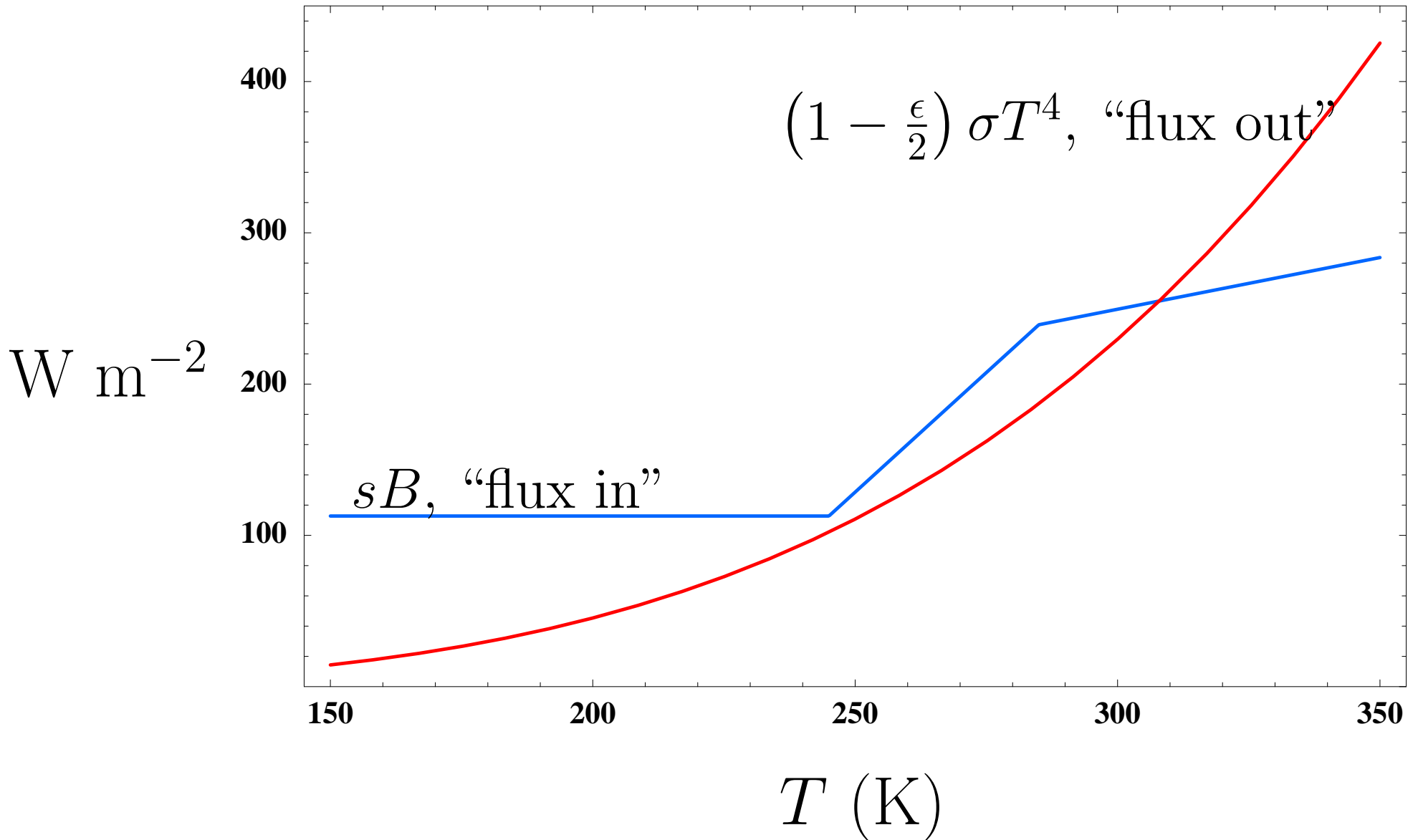
$$B(T) = \begin{cases} 0.33 & : T \leq 245 \\ 0.33 + .00925 \times (T - 245) & : 245 < T \leq 285 \\ 0.7 + .002 \times (T - 285) & : T > 285 \end{cases}$$

$$s = \frac{1}{4} S_0 \quad C = H \rho_w c_w \quad H = 2738 \text{ m}$$

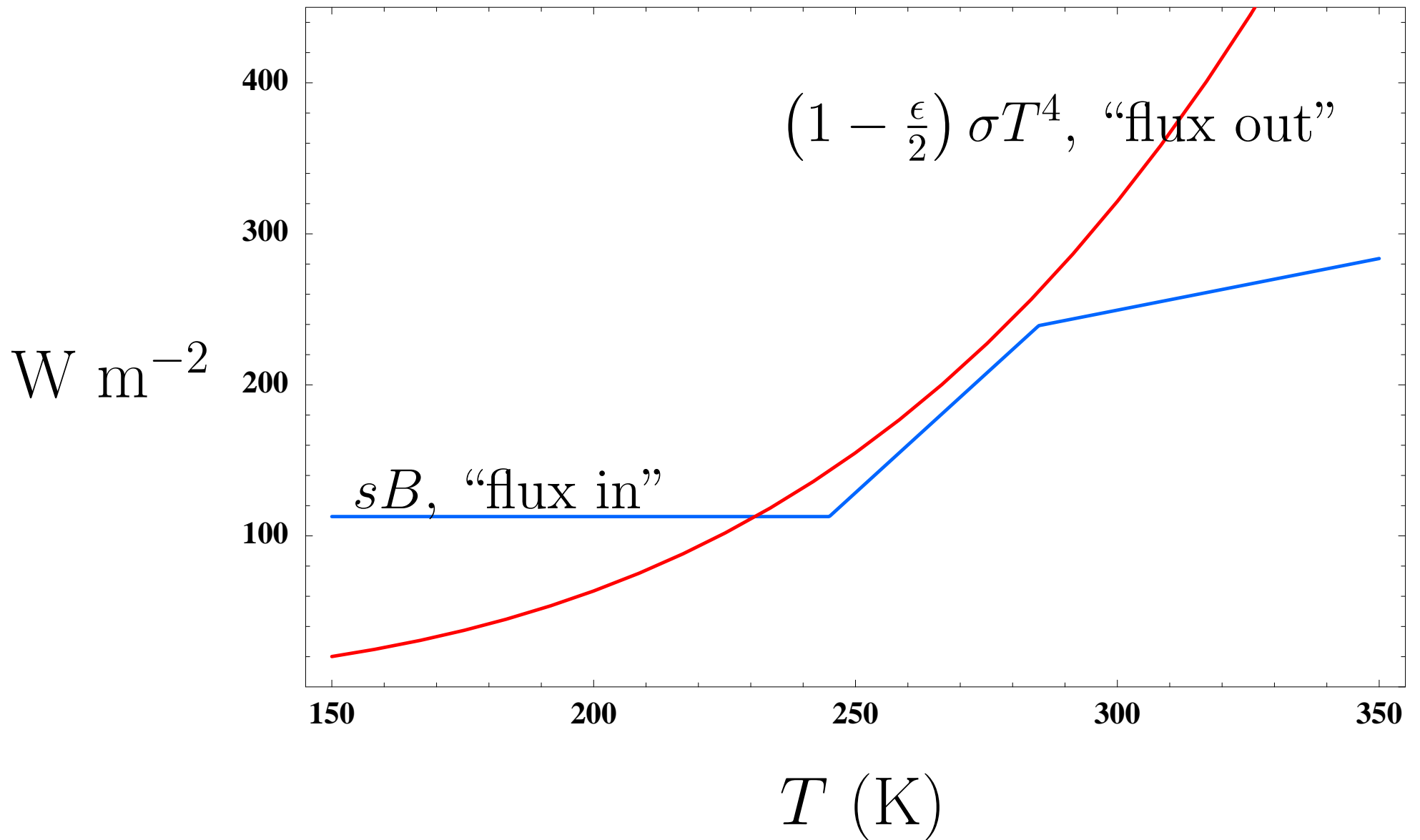
$\epsilon = .80$ , three equilibria possible



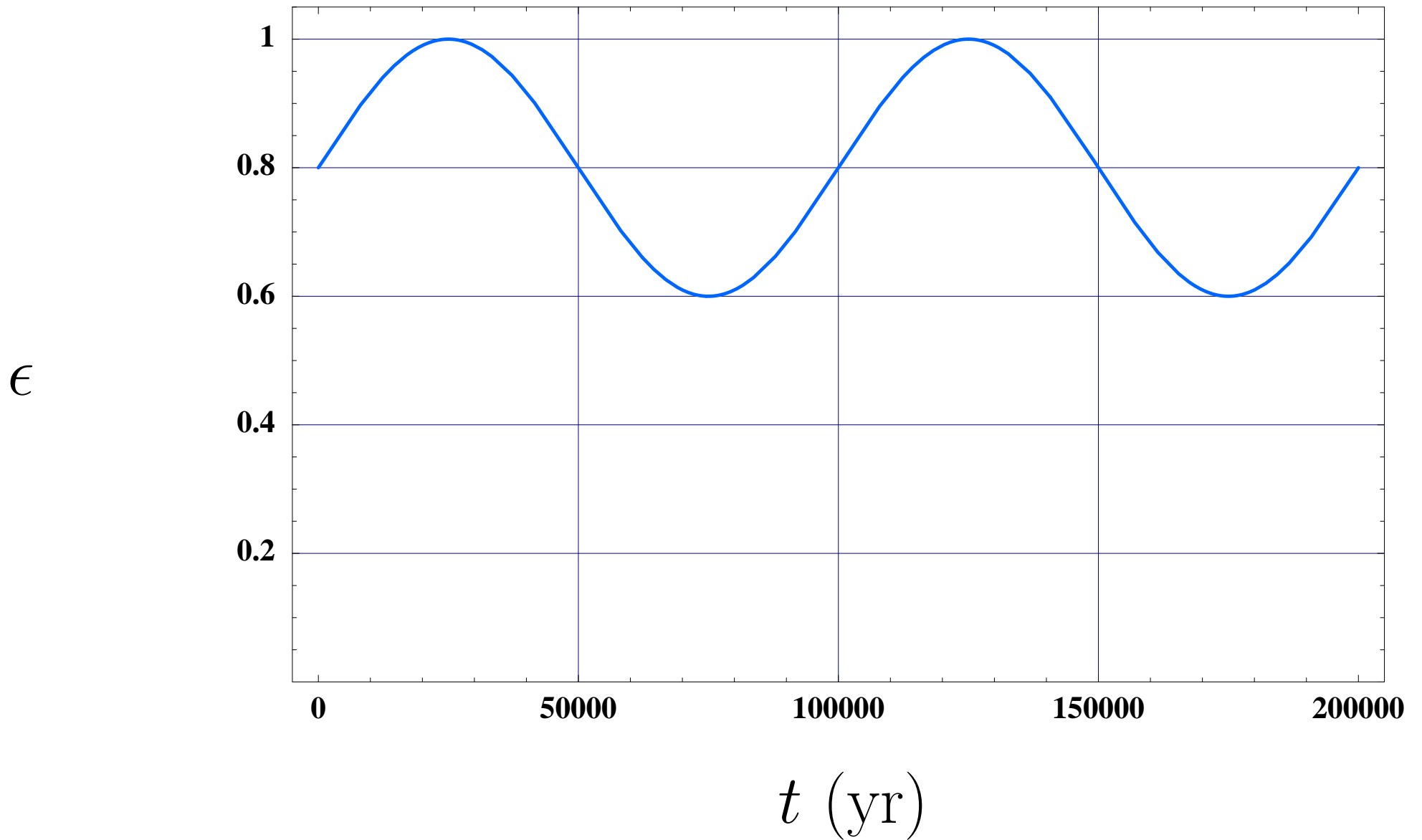
$\epsilon = 1.0$ , only de-iced equilibrium possible



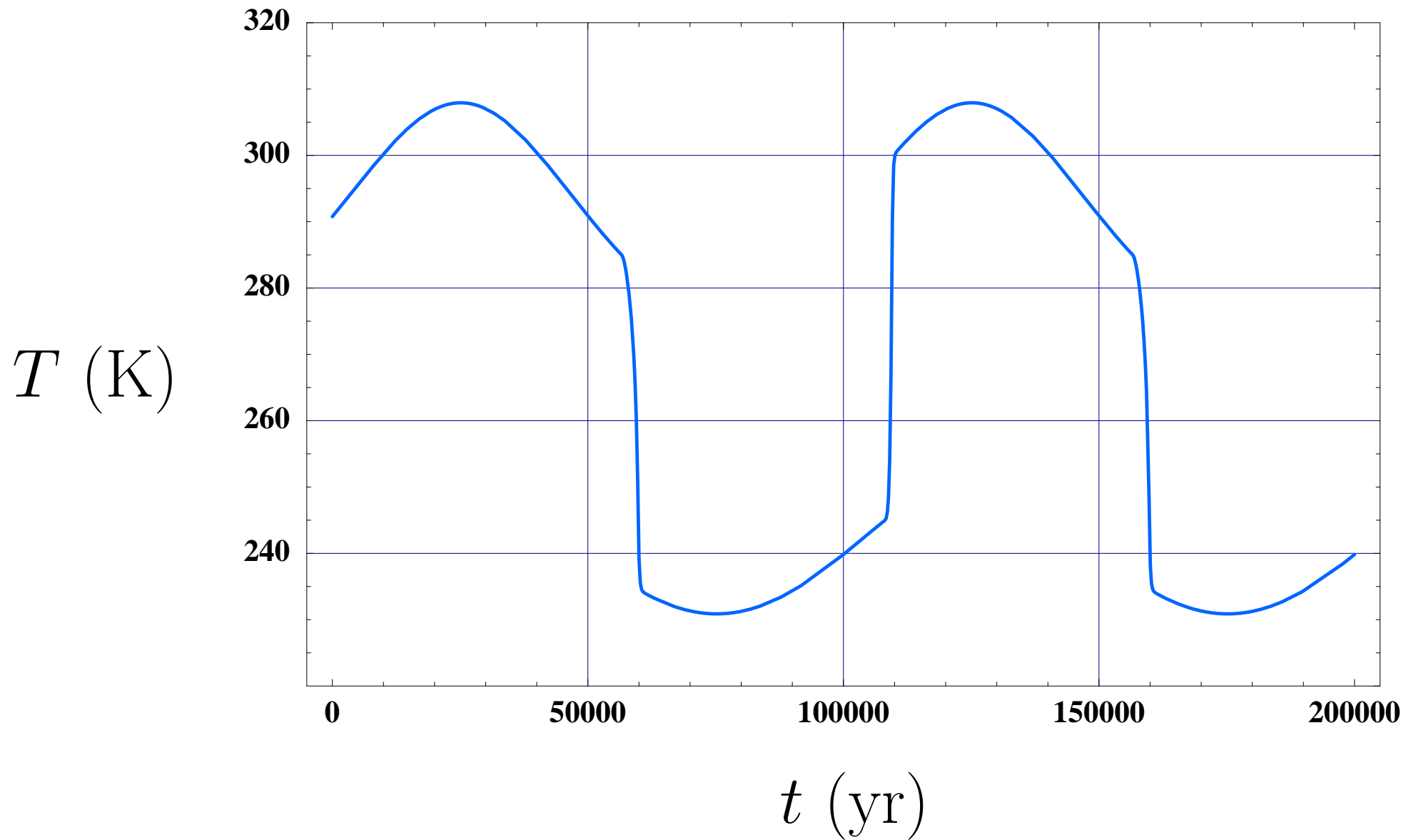
$\epsilon = 0.6$ , only snowball possible



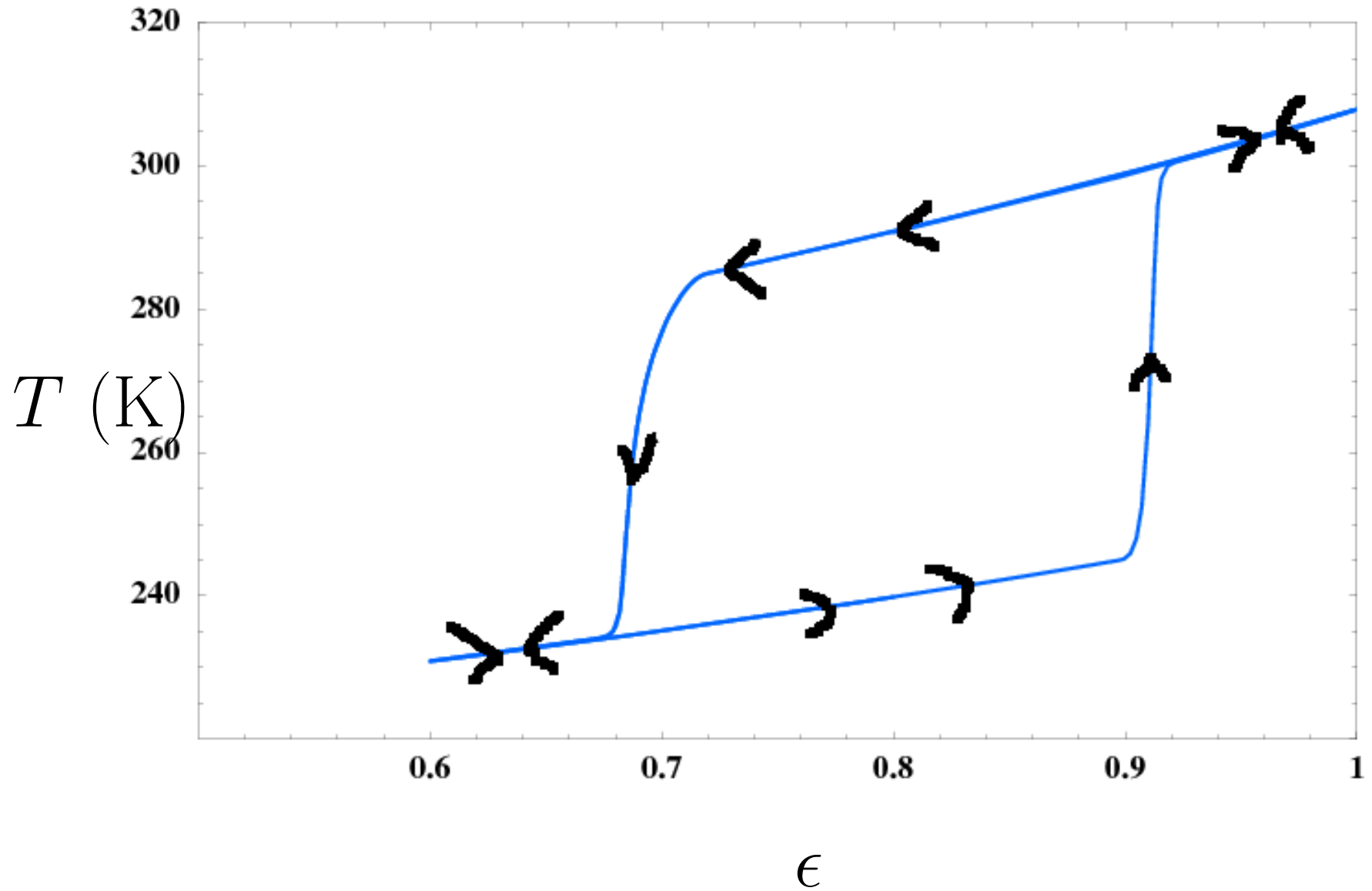
hypothetical variation of  $\epsilon(t)$



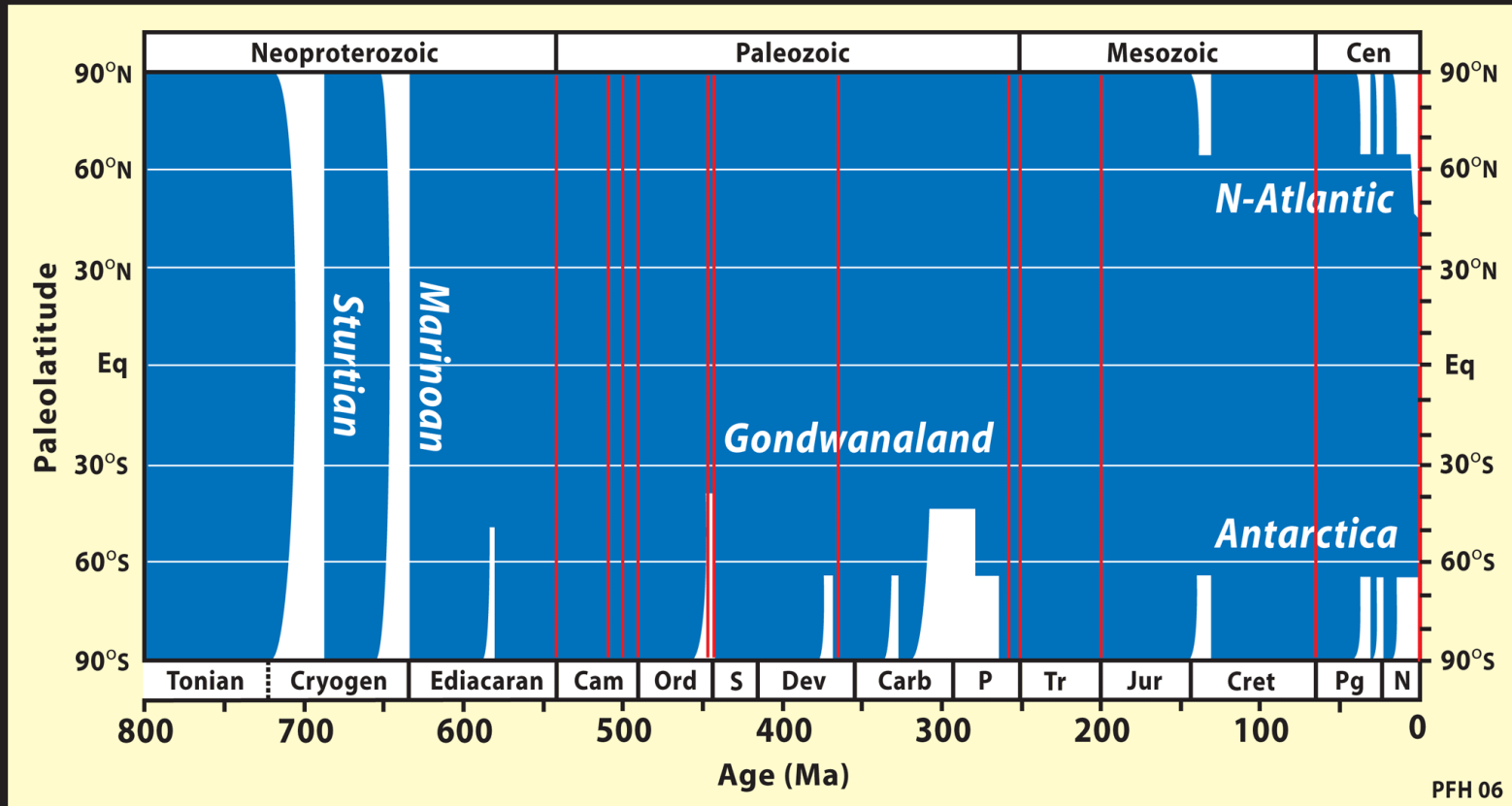
response  $T(t)$  to  $\epsilon(t)$



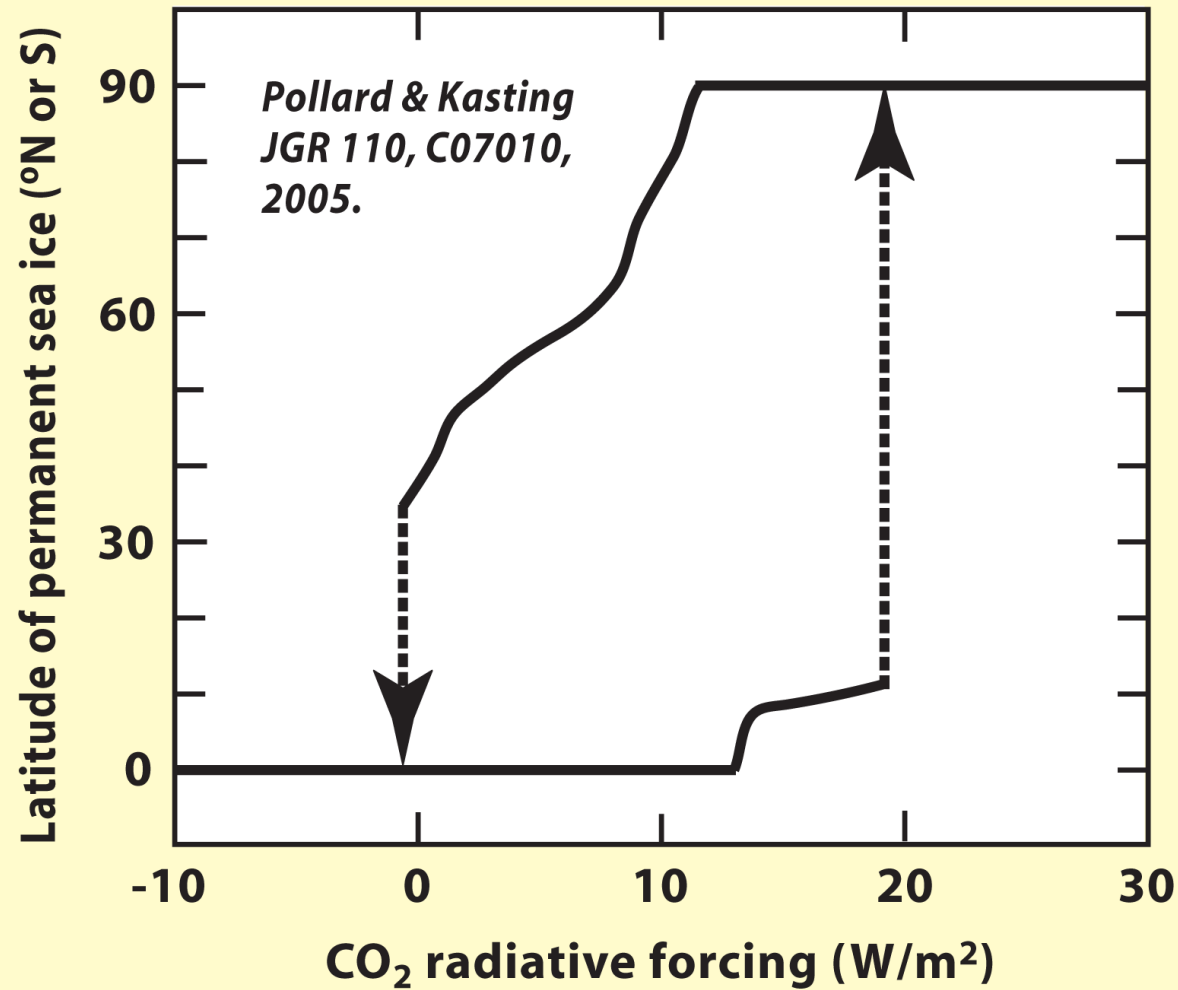
hysteresis of  $T(t)$  with  $\epsilon(t)$



**Paleogeographic extent of continental ice sheets and permanent sea ice over the last 800 Myr (red lines indicate major mass extinctions)**



<http://www.snowballearth.org>



*EBM with fully-coupled sea-ice dynamics on an all-ocean planet : solution with 2200-km-wide equatorial zone of thin (<2 m) ice (only stable when ablative ice is bubble-free). Magnitude of CO<sub>2</sub> hysteresis is far less than for thick tropical ice solutions when the ablative ice is bubbly.*

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