Revisiting the geologic carbon cycle

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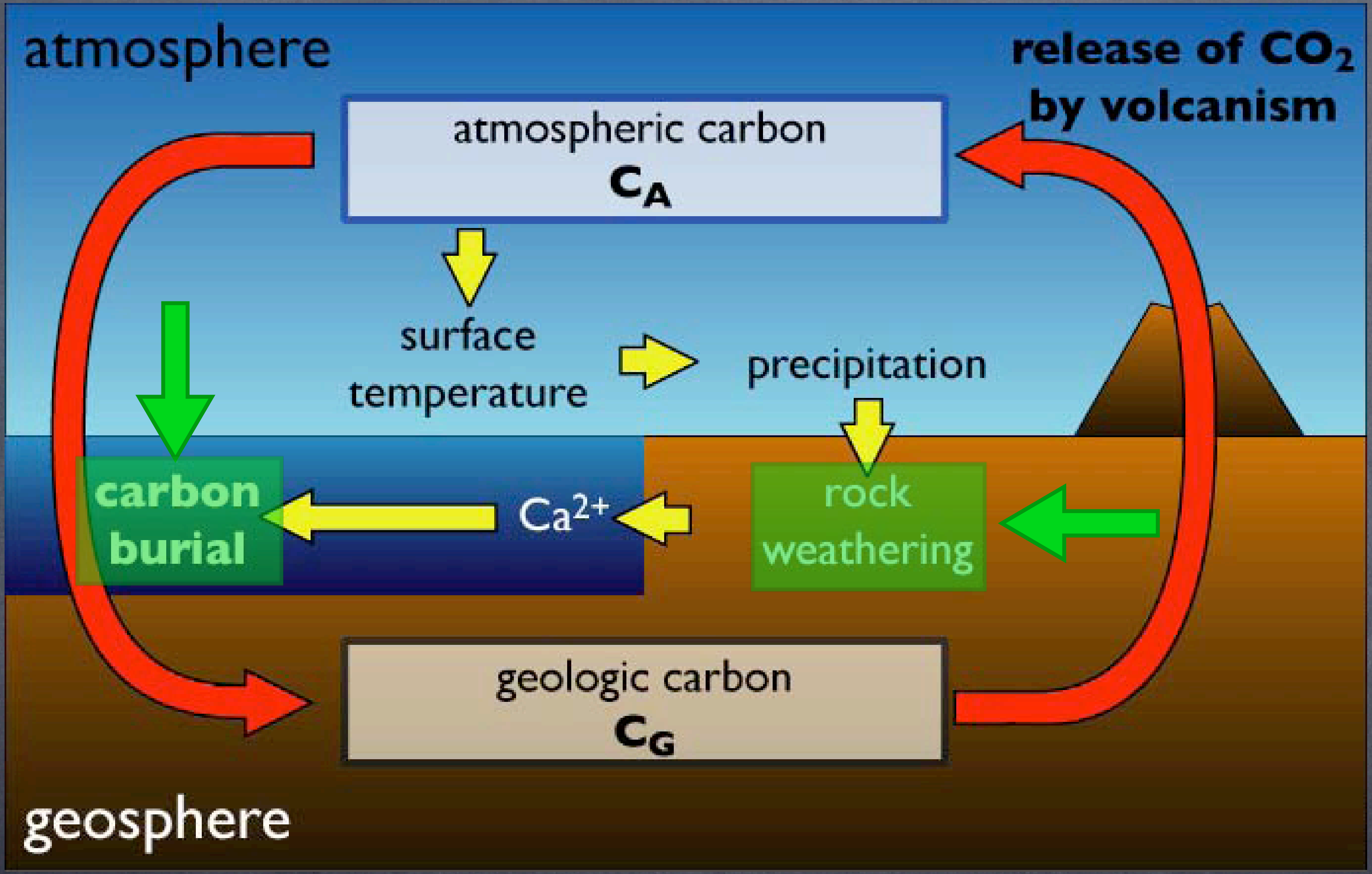

atmosphere
release of CO_2 by volcanism
atmospheric carbon
C_A
surface temperature
precipitation
carbon burial
Ca^{2+}
rock weathering
geologic carbon
C_G
geosphere

Two competing threads...

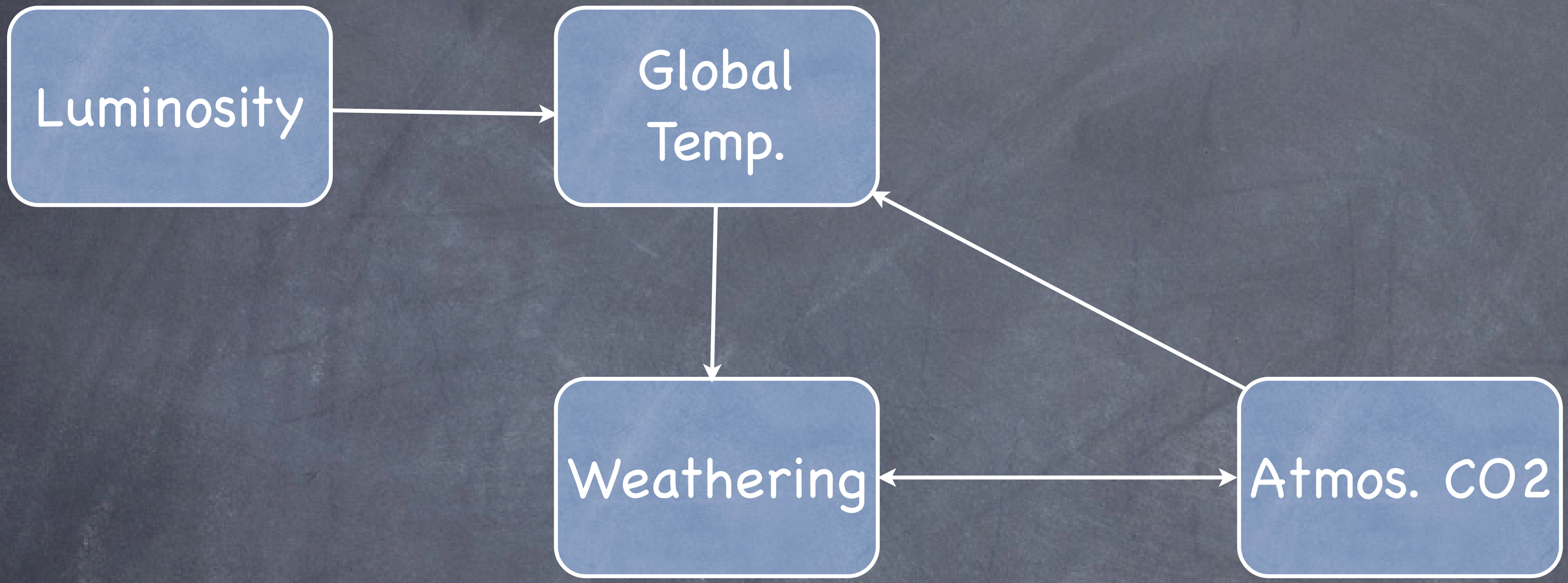
- Berner, Lasaga and Garrels (1983) - BLAG - More complex, time-dependent, eventually morphed in GEOCARB
- Walker, Hays, Kastings (1981) - WHAK - Simple algebraic expressions, steady state, balances weathering with outgassing

Walker et al (1981)

$$\frac{dC_{atm}}{dt} = V - W = 0$$

$$\frac{R}{R_0} = \exp\left(\frac{\Delta T}{60}\right) \quad \frac{M}{M_0} = \exp\left(\frac{\Delta T}{17.7}\right)$$

$$\frac{W}{W_0} = \frac{C_{atm}}{C_{atm,0}} \exp\left(\frac{\Delta T}{13.7}\right)$$


Luminosity
Global Temp.
Weathering
Atmos. CO2

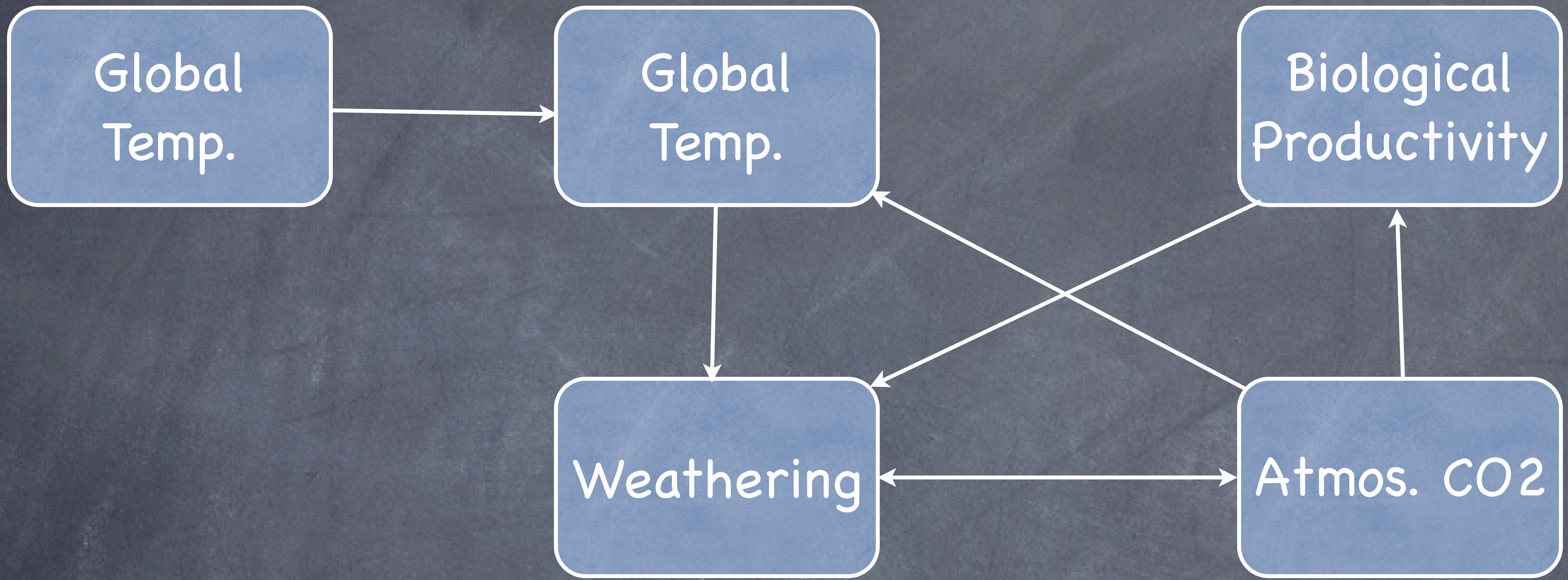
Volk (1987)

- Extends the WHAK model by using soil CO2 concentrations and expressing biological productivity as a hyperbolic function of CO2.
- Compares and contrasts the BLAG and WHAK approaches.

$$\frac{W}{W_0} = \frac{C_{soil}}{C_{soil,0}} \exp\left(\frac{\Delta T}{13.7} \right)$$

$$\frac{C_{soil}}{C_{soil,0}} = \frac{\Pi}{\Pi_0}\left(1 - \frac{C_{atm,0}}{C_{soil,0}}\right) + \frac{C_{atm}}{C_{soil,0}}$$

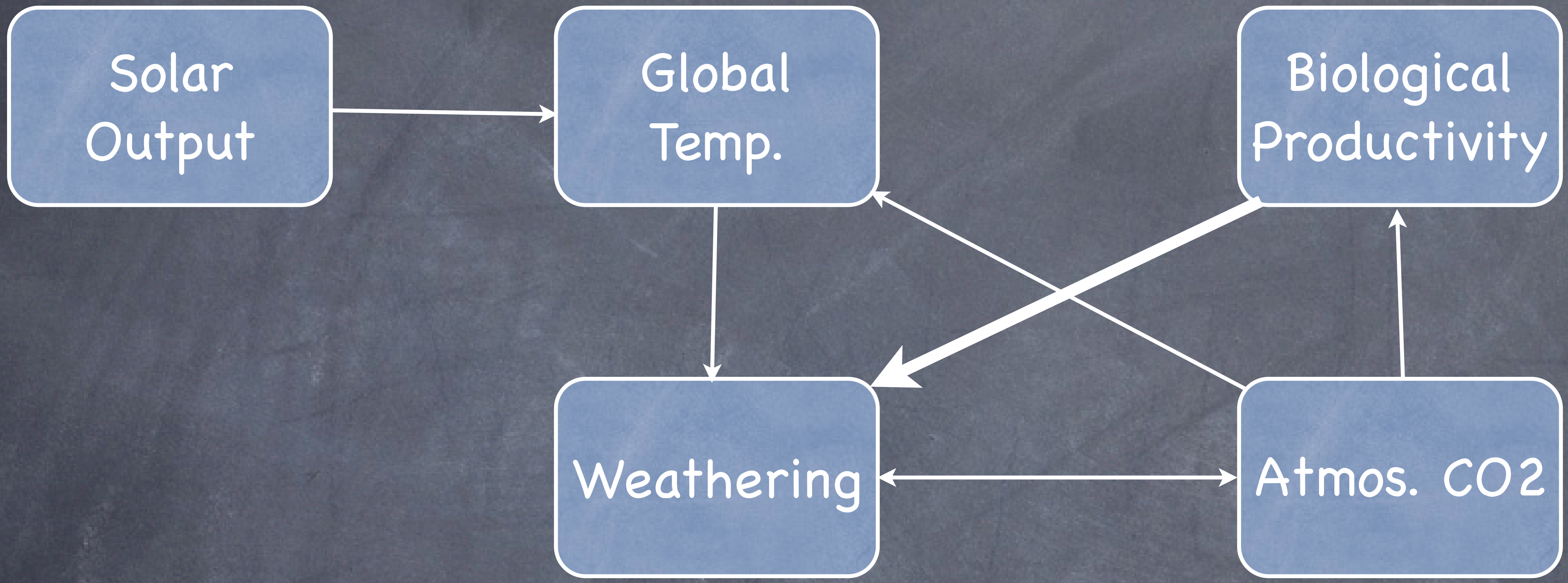
$$\Pi = \Pi_{max}\left(\frac{C_{atm} - C_{min}}{C_{half} + (C_{atm} - C_{min})} \right)$$


Global Temp.
Global Temp.
Biological Productivity
Weathering
Atmos. CO2

Schwartzman and Volk (1989)

$$\frac{W}{W_0} = B\left(\frac{C_{soil}}{C_{soil,0}}\right)\exp\left(\frac{\Delta T}{13.7}\right)$$

- Schwartzmann and Volk (1989) introduce a biotic enhancement factor, B.
- They show that increased soil CO2 only accounts for a 2 to 6 fold increase in weathering rates over abiotic conditions, however, biota appear to responsible for enhancing the rates at least 10 fold and more likely closer to 100x.


Solar Output
Global Temp.
Biological Productivity
Weathering
Atmos. CO2

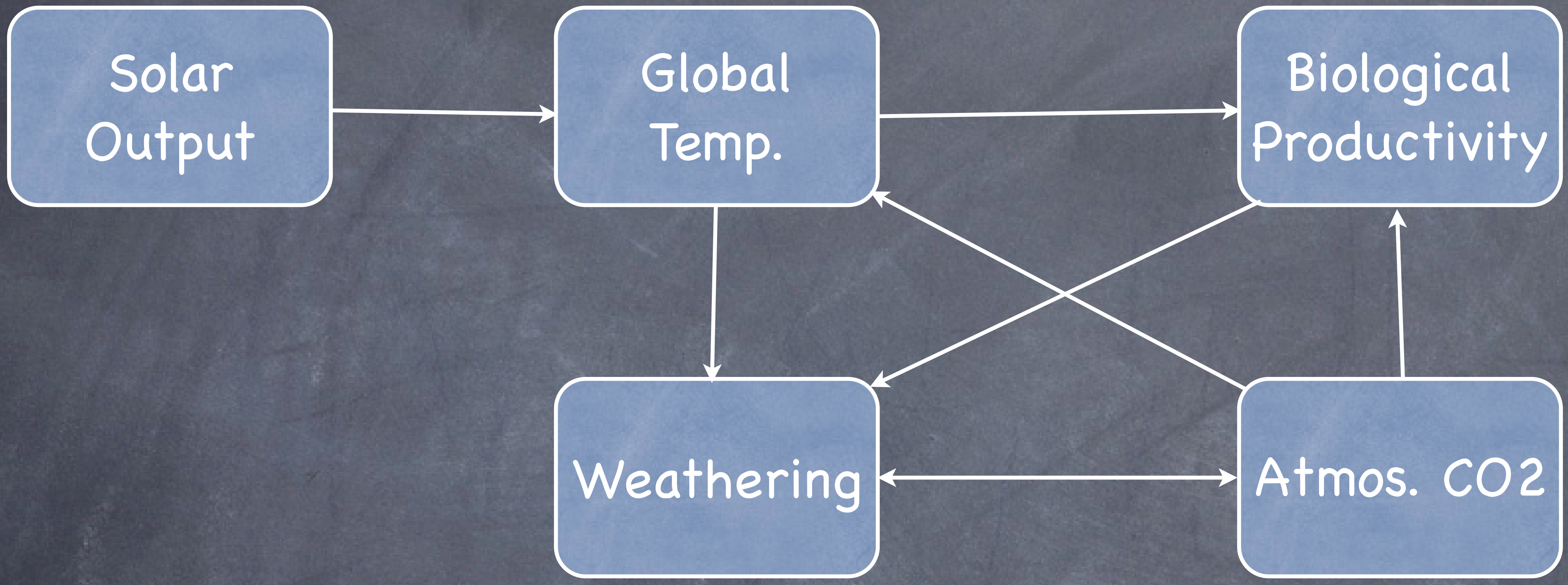
Caldeira and Kastings (1992)

- Uses WHAK model to investigate life span of the biosphere.
- Adds temperature dependence to productivity.
- Purports that biosphere has 1.5 Gyr left before CO2 falls below minimum for C4 photosynthesis

$$\Pi = \Pi_{max} \cdot \Pi_T \cdot \Pi_C$$

$$\Pi_T = \begin{cases} 1 - \left(\frac{T - 25}{25} \right) & \text{for } 0 < T < 50 \\ 0 & \text{else} \end{cases}$$

$$\Pi_C = \begin{cases} \frac{C_{atm} - C_{min}}{C_{half} + (C_{atm} - C_{min})} & \text{for } C_{atm} > C_{min} \\ 0 & \text{else} \end{cases}$$


Solar Output
Global Temp.
Biological Productivity
Weathering
Atmos. CO2

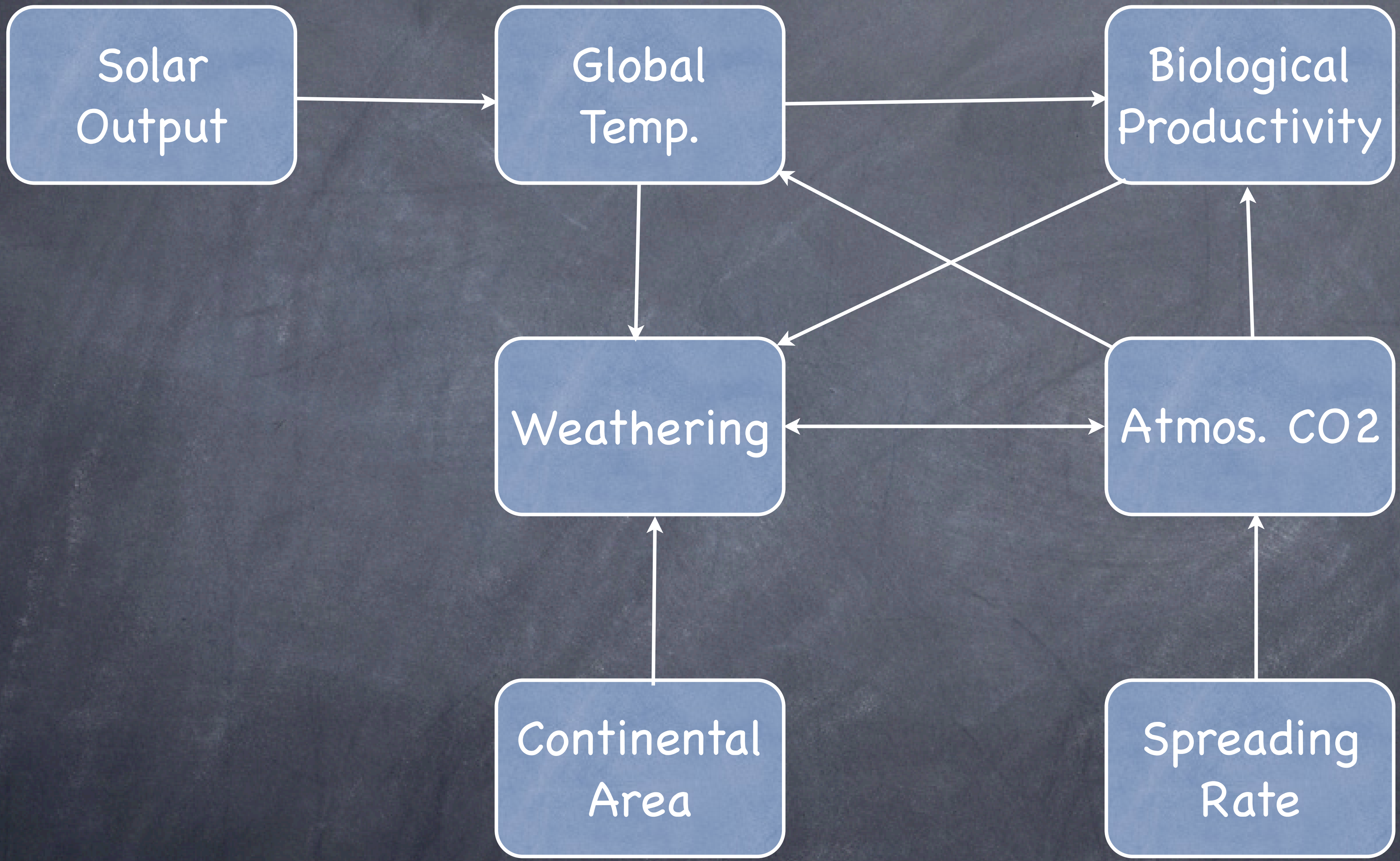
Franck et al (1999,2000)

- Earlier versions assumed static volcanic activity, Franck et al add geodynamics including continental growth model and variable seafloor spreading rates.
- Geodynamics reduce the potential lifespan of the biosphere to 900 Myr.

$$V = V_0 \cdot \frac{S}{S_0}$$

$$A_{earth} = A_{ocean}(t) + A_{continent}(t)$$

$$S(t) = \frac{q_m(t)^2 \pi k A_{ocean}(t)}{(2k (T_m(t) - T_{s,0}))^2}$$


Solar Output
Global Temp.
Biological Productivity
Weathering
Atmos. CO2
Continental Area
Spreading Rate

Extraterrestrial Gaias

- $Ngaia = N_{mw} * f_p * N_{chz} * f_l$
- Using a conservative estimate for the fraction of planets where life occurs results in 4.8 * 10^5 sister planets (Franck et al. 2001)

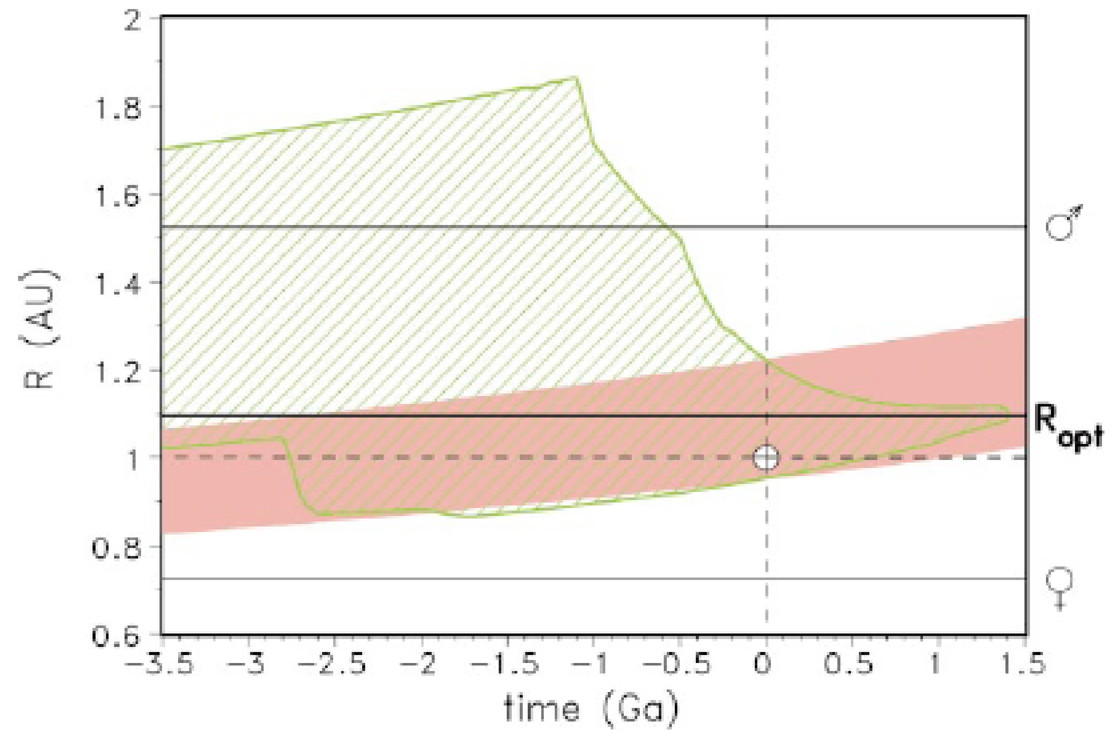


Fig. 5. Evolution of the HZ for GSM (red) and GDM (green). The optimum position of an Earth-like planet is at $R_{opt} = 1.08$ AU. In this case the life span of the biosphere is at maximum. The total amount of carbon, P_{CO_2}(total), is 10 bar and the optimum temperature for the biosphere, T_{opt}, is 25°C.

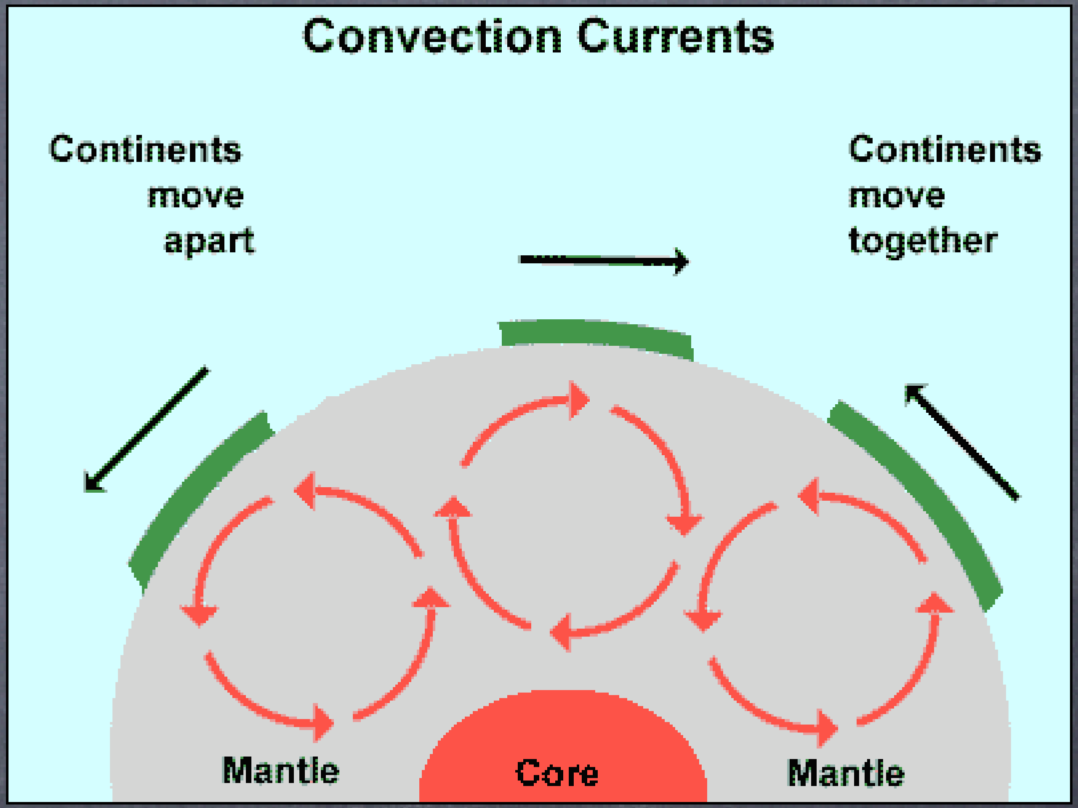
My Current Work

- Lenardic (2005): MEP and optimal continental growth
- MEP and optimal biotic enhancement (e.g. Kleidon 2004)
- Ice sheets: inhibit or enhance weathering?

Optimum Continental Area

Optimize Aocean to maximize mantle heat flow, Qm

$$S(t) = \frac{q_m(t)^2 \pi k A_{ocean}(t)}{(2k (T_m(t) - T_{s,0}))^2}$$



Continental crust insulates mantle, higher temperatures lead to decreased viscosity and overall higher heat flow.

Optimum Biotic Enhancement

$$\frac{W}{W_0} = B\left(\frac{C_{soil}}{C_{soil,0}}\right)\exp\left(\frac{\Delta T}{13.7}\right)$$

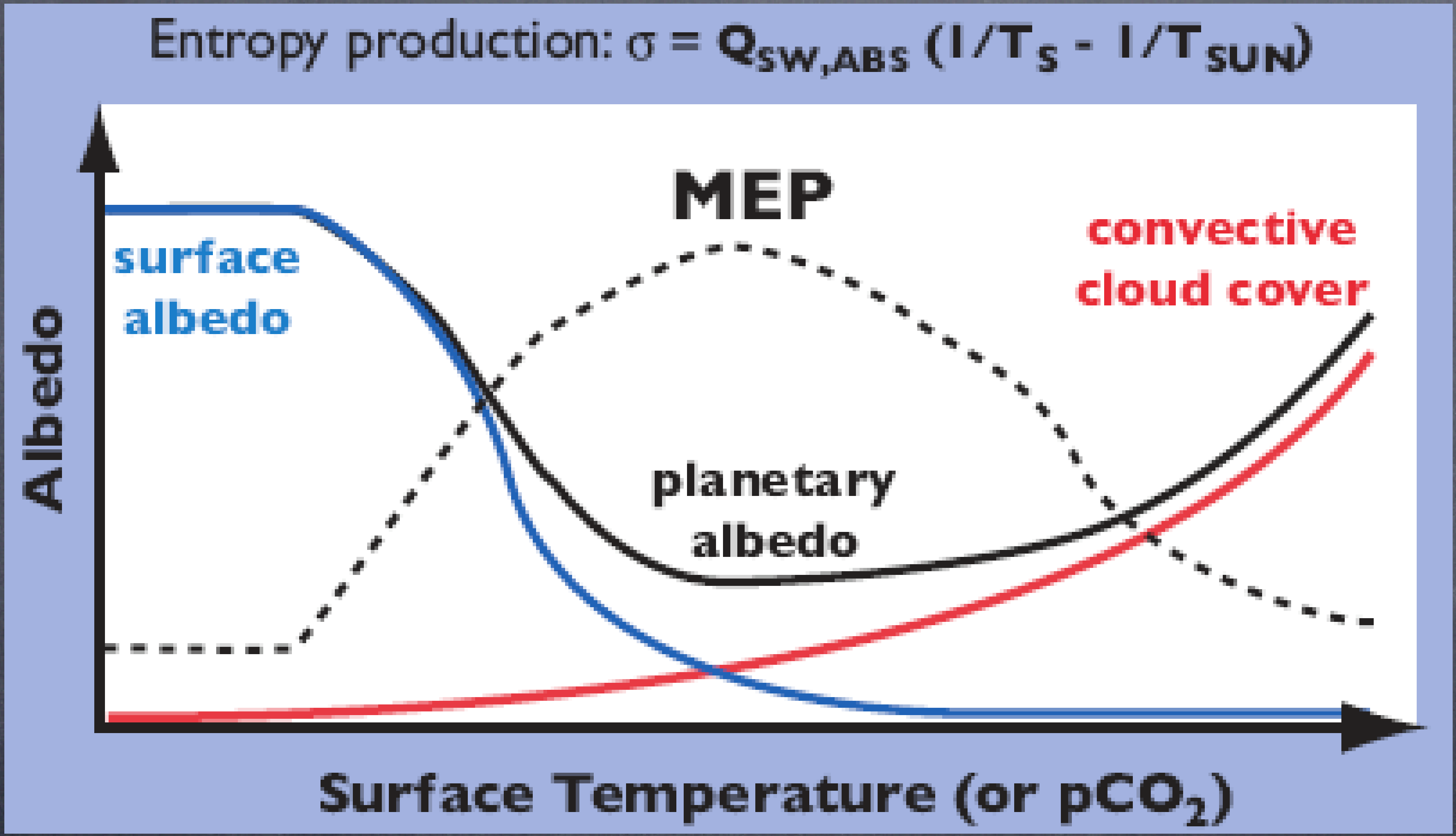
- Optimize biotic enhancement factor, B, to maximize productivity.
- Previous studies by Schwartzman and Volk (1989) and Schwartman (2003) show large space of possible rates of biotic enhancement.
- Biotic enhancement is a macroscopic parameter, scaling up many smaller diabatic processes and thus MEP should apply here.

Ice

- Weathering is severely retarded beneath ice sheets.
- This has been suggested as the cause of the termination of Snowball Earth events.
- Volcanic outgassing continues while weathering slows to a halt, allowing greenhouse gases to pile up in the atmosphere, which eventually lead to a runaway deglaciation.
- On a shorter timescale, however, glacial-interglacial episodes scrape the surface revealing new unweathered rock.

Additions to the model

- W/W0 = B * (Catm/Catm0) * M/M0 * min(2,R/R0) * Ac/Ac0 * (1-fice/1-fice0)
- Splitting the albedo component of the energy balance in to two boxes, tropical and polar
- Adding a new light-limitation based on cloudiness to productivity term
- Adding a land ice component using parameterization developed with many sensitivity simulations from an Earth System Model of


Entropy production: σ = Q_SW,ABS (1/T_S - 1/T_SUN)
MEP
surface albedo
convective cloud cover
planetary albedo
Albedo
Surface Temperature (or pCO₂)