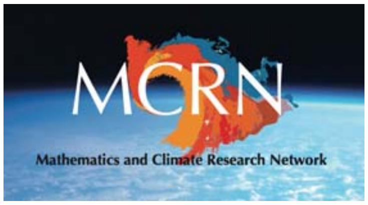
An Introduction to Budyko's Model

Richard McGehee
School of Mathematics
University of Minnesota

Mathematics of Climate Seminar
September 19, 2017



Budyko's Model

Dynamical Models

Add Heat Transport $R\frac{\partial T}{\partial t} = Qs(y)(1-\alpha) - (A+BT) + C(\bar{T} - T)$

global mean temperature $\bar{T}(t) = \int_0^1 T(y,t)dy$

Second Law of Thermodynamics:
Energy travels from hot places to cold places.

Equilibrium temperature profile?

Budyko's Model

Conservation of Energy

temperature change ~ energy in – energy out

energy in: short wave energy from the Sun
energy out: long wave energy from the Earth

Everything else is detail.

Budyko's Model

Budyko's Equation

$$R\frac{\partial T}{\partial t} = Qs(y)(1-\alpha(y)) - (A+BT) + C(\bar{T} - T)$$

- surface temperature: T
- heat capacity: R
- insolation: $Qs(y)$
- sin(latitude): y
- albedo: $\alpha(y)$
- OLR: $A+BT$
- heat transport: $C(\bar{T} - T)$, with $\bar{T} = \int_0^1 T(y)dy$

Symmetry assumption: $0 \le y = \sin(\text{latitude}) \le 1$

Chylek and Coakley's quadratic approximation:

$s(y) \approx 1 - 0.241(3y^2 - 1)$

Budyko's Model

Dynamical Models

	Model	Equilibrium
Perfectly Thermally Conducting Black Body	$R\frac{dT}{dt} = Q - \sigma T^4$	$T = (Q/\sigma)^{1/4}$
Plus Albedo	$R\frac{dT}{dt} = Q(1-\alpha) - \sigma T^4$	$T = ((1-\alpha)Q/\sigma)^{1/4}$
Switch to Surface Temperature	$R\frac{dT}{dt} = Q(1-\alpha) - (A+BT)$	$T = ((1-\alpha)Q - A)/B$
Dependence on Latitude	$R\frac{\partial T(y,t)}{\partial t} = Qs(y)(1-\alpha) - (A+BT(y,t))$	$T(y) = ((1-\alpha)Qs(y) - A)/B$

Budyko's Model

Budyko's Equilibrium

$$R\frac{\partial T}{\partial t} = Qs(y)(1-\alpha(y)) - (A+BT) + C(\bar{T} - T)$$

albedo depends on latitude

equilibrium solution: $T = T^*(y)$

$$Qs(y)(1-\alpha(y)) - (A + BT^*(y)) + C(\bar{T}^* - T^*(y)) = 0$$

Integrate:

$$\int_0^1 \left(Qs(y)(1-\alpha(y)) - (A + BT^*(y)) + C(\bar{T}^* - T^*(y))\right)dy = 0$$

$$Q\underbrace{\int_0^1 s(y)dy}_{1} - Q\underbrace{\int_0^1 s(y)\alpha(y)dy}_{\bar{\alpha}} - A\underbrace{\int_0^1 dy}_{1} - B\underbrace{\int_0^1 T^*(y)dy}_{\bar{T}^*} + C\left(\underbrace{\int_0^1 \bar{T}^* dy}_{\bar{T}^*} - \underbrace{\int_0^1 T^*(y)dy}_{\bar{T}^*}\right) = 0$$

$$Q(1-\bar{\alpha}) - (A + B\bar{T}^*) = 0$$

equilibrium global mean temperature $\boxed{\bar{T}^* = \frac{1}{B}\left(Q(1-\bar{\alpha}) - A\right)}$

Budyko's Model

Budyko's Equilibrium

$$Qs(y)(1-\alpha(y)) - (A + BT^*(y)) + C(\overline{T}^* - T^*(y)) = 0$$

Global mean temperature at equilibrium:

$$\overline{T}^* = \frac{1}{B}(Q(1-\overline{\alpha}) - A) \qquad \left(\overline{\alpha} = \int_0^1 \alpha(y)s(y)dy\right)$$

Solve for $T^*(y)$.

$$Qs(y)(1-\alpha(y)) - A + C\overline{T}^* = BT^*(y) + CT^*(y) = (B+C)T^*(y)$$

$$T^*(y) = \frac{1}{B+C}(Qs(y)(1-\alpha(y)) - A + C\overline{T}^*)$$

Equilibrium temperature profile:

$$\boxed{T^*(y) = \frac{1}{B+C}(Qs(y)(1-\alpha(y)) - A + C\overline{T}^*)}$$

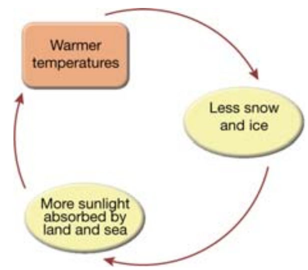
where $\overline{T}^* = \frac{1}{B}(Q(1-\overline{\alpha}) - A)$ and $\overline{\alpha} = \int_0^1 \alpha(y)s(y)dy$

Budyko's Model

Ice Albedo Feedback

temperature warms
ice melts
albedo decreases
more sunlight absorbed
temperature warms
REPEAT

Why would it stop?



http://www.i-fink.com/melting-polar-ice/

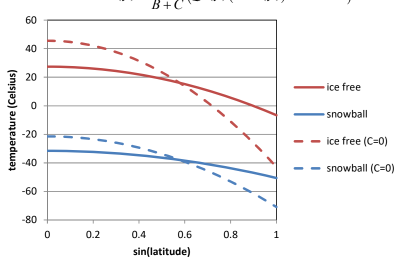
Budyko's Model

Budyko's Equilibrium

$$Qs(y)(1-\alpha(y)) - (A + BT^*(y)) + C(\overline{T}^* - T^*(y)) = 0$$

Equilibrium temperature profile: $T^*(y) = \frac{1}{B+C}(Qs(y)(1-\alpha(y)) - A + C\overline{T}^*)$

$C = 3.04$
$\alpha(y) = 0.32$: ice free
$\alpha(y) = 0.62$: snowball
(constant albedo)



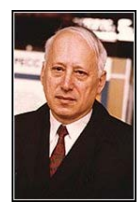
Budyko's Model

Ice Albedo Feedback

M. I. Budyko, "The effect of solar radiation variations on the climate of the Earth," **Tellus XXI**, 611-619 , 1969.

temperature warms
ice melts
albedo decreases
more sunlight absorbed
temperature warms
REPEAT

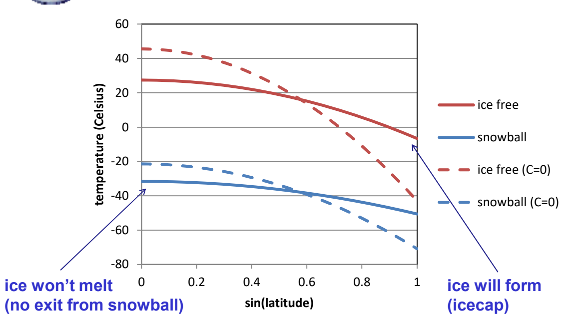
Why would it stop?



http://www.inenco.org/index_principals.html

Budyko's Model

Budyko's Equilibrium



Budyko's Model

Ice Albedo Feedback

Why would it stop?

Budyko's Equation

$$R\frac{\partial T}{\partial t} = Qs(y)(1-\alpha(y)) - (A+BT) + C(\overline{T} - T)$$

$$\overline{T} = \int_0^1 T(y)dy$$

surface temperature; sin(latitude); heat capacity; insolation; albedo; OLR; heat transport

Budyko's Model

Ice Albedo Feedback

What if the albedo is not constant?

Ice Line Assumption: There is a single ice line at $y=\eta$ between the equator and the pole. The albedo is α_1 below the ice line and α_2 above it.

$$\alpha(y,\eta)=\begin{cases}\alpha_1 & y<\eta\\ \alpha_2 & y>\eta\end{cases}$$

Equilibrium condition:

$$Qs(y)\big(1-\alpha(y,\eta)\big)-\big(A+BT_\eta^*(y)\big)+C\big(\overline{T}^*-T_\eta^*(y)\big)=0$$

Equilibrium solution:

$$T_\eta^*(y)=\frac{1}{B+C}\Big(Qs(y)\big(1-\alpha(y,\eta)\big)-A+C\overline{T}_\eta^*\Big)$$

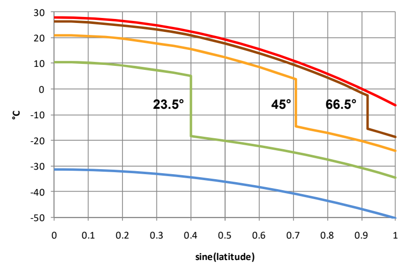
where $\overline{T}_\eta^*=\frac{1}{B}\big(Q(1-\overline{\alpha}(\eta))-A\big)$ $\quad\Big(\overline{\alpha}(\eta)=\int_0^1\alpha(y,\eta)s(y)dy\Big)$

Budyko's Model

Ice Albedo Feedback

$$T_\eta^*(y)=\frac{1}{B+C}\Big(Qs(y)\big(1-\alpha(y,\eta)\big)-A+C\overline{T}_\eta^*\Big)$$

For each fixed η, there is an equilibrium solution for Budyko's equation



Budyko's Model

Ice Albedo Feedback

equilibrium temperature profile:

$$T_\eta^*(y)=\frac{1}{B+C}\Big(Qs(y)\big(1-\alpha(y,\eta)\big)-A+C\overline{T}_\eta^*\Big),\ \text{where}\ \ \overline{T}_\eta^*=\frac{1}{B}\big(Q(1-\overline{\alpha}(\eta))-A\big)$$

albedo:
$$\alpha(y,\eta)=\begin{cases}\alpha_1=0.32, & y<\eta\\ \alpha_2=0.62, & y>\eta\end{cases}$$

global albedo:
$$\overline{\alpha}(\eta)=\int_0^1\alpha(y,\eta)s(y)dy=\int_0^\eta\alpha_1 s(y)dy+\int_\eta^1\alpha_2 s(y)dy$$

let:
$$S(\eta)=\int_0^\eta s(y)dy,\quad 1-S(\eta)=\int_\eta^1 s(y)dy,\quad \text{since}\quad 1=\int_0^1 s(y)dy$$

then:
$$\overline{\alpha}(\eta)=\alpha_1 S(\eta)+\alpha_2(1-S(\eta))=\alpha_2-(\alpha_2-\alpha_1)S(\eta)=0.62-0.3S(\eta)$$

$$S(\eta)=\int_0^\eta s(y)dy=\underbrace{\int_0^\eta\big(1-0.241\big(3y^2-1\big)\big)dy}_{\text{Chylek \& Coakley}}=\eta-0.241\big(\eta^3-\eta\big)$$

Budyko's Model

Dynamics

$$R\frac{\partial T}{\partial t}=Qs(y)(1-\alpha(y))-(A+BT)+C(\overline{T}-T)$$

Let X be the space of functions where T lives. (*e.g.* $L^1([0,1])$)
Let

$$L:X\to X:LT=C\overline{T}-(B+C)T,$$
$$f(y)=Qs(y)\big(1-\alpha(y)\big)-A$$

Budyko's equation can be written as a linear vector field on X.

$$R\frac{dT}{dt}=f+LT$$

The operator L has only point spectrum, with all eigenvalues negative.
Therefore, all solutions are stable.
True for any albedo function.

experts only

Budyko's Model

Ice Albedo Feedback

equilibrium temperature profile:

$$\boxed{T_\eta^*(y)=\frac{1}{B+C}\Big(Qs(y)\big(1-\alpha(y,\eta)\big)-A+C\overline{T}_\eta^*\Big)},\ \text{where}\ \ \boxed{\overline{T}_\eta^*=\frac{1}{B}\big(Q(1-\overline{\alpha}(\eta))-A\big)}$$

albedo:
$$\alpha(y,\eta)=\begin{cases}\alpha_1=0.32, & y<\eta\\ \alpha_2=0.62, & y>\eta\end{cases}$$

global albedo:
$$\overline{\alpha}(\eta)=\int_0^1\alpha(y,\eta)s(y)dy=\int_0^\eta\alpha_1 s(y)dy+\int_\eta^1\alpha_2 s(y)dy$$

let:
$$S(\eta)=\int_0^\eta s(y)dy,\quad 1-S(\eta)=\int_\eta^1 s(y)dy,\quad \text{since}\quad 1=\int_0^1 s(y)dy$$

then:
$$\boxed{\overline{\alpha}(\eta)}=\alpha_1 S(\eta)+\alpha_2(1-S(\eta))=\alpha_2-(\alpha_2-\alpha_1)S(\eta)=\boxed{0.62-0.3S(\eta)}$$

$$\boxed{S(\eta)}=\int_0^\eta s(y)dy=\underbrace{\int_0^\eta\big(1-0.241\big(3y^2-1\big)\big)dy}_{\text{Chylek \& Coakley}}=\boxed{\eta-0.241\big(\eta^3-\eta\big)}$$

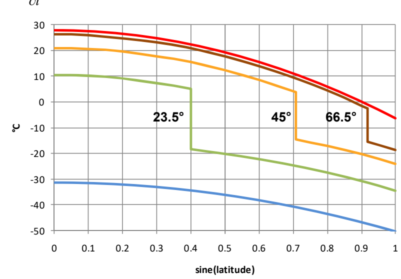
Budyko's Model

Ice Albedo Feedback

$$R\frac{\partial T}{\partial t}=Qs(y)(1-\alpha(y,\eta))-(A+BT)+C(\overline{T}-T)$$

For each fixed η, there is a **globally stable** equilibrium solution for Budyko's equation.

How to pick one?



Budyko's Model

Ice Albedo Feedback

Summary

If we artificially hold the ice line at a fixed latitude, then the surface temperature will come to an equilibrium.

However,
if the temperature is high, we would expect ice to melt and the ice line to retreat to higher latitudes. If the temperature is low, we would expect ice to form and the ice line to advance to lower latitudes.

How to model this expectation?

Budyko's Model

Ice Albedo Feedback

$$R\frac{\partial T}{\partial t} = Qs(y)(1-\alpha(y,\eta)) - (A+BT) + C(\overline{T}-T)$$

Equilibrium: $$T_\eta^*(y) = \frac{1}{B+C}\left(Qs(y)\left(1-\alpha(y,\eta)\right) - A + C\overline{T}_\eta^*\right)$$

Ice line condition: $$\frac{1}{2}\left(T_\eta^*(\eta+) + T_\eta^*(\eta-)\right) = T_c = -10$$

Albedo: $$\alpha(y,\eta) = \begin{cases} \alpha_1 = 0.32, & y < \eta \\ \alpha_2 = 0.62, & y > \eta \end{cases} \qquad \alpha(\eta-,\eta) = \alpha_1, \quad \alpha(\eta+,\eta) = \alpha_2$$

$$T_\eta^*(\eta+) = \frac{1}{B+C}\left(Qs(\eta)\left(1-\alpha_2\right) - A + C\overline{T}_\eta^*\right) \qquad T_\eta^*(\eta-) = \frac{1}{B+C}\left(Qs(\eta)\left(1-\alpha_1\right) - A + C\overline{T}_\eta^*\right)$$

Ice line condition:

$$\frac{1}{2}\left(T_\eta^*(\eta+) + T_\eta^*(\eta-)\right) = \frac{1}{B+C}\left(Qs(\eta)\left(1-\alpha_0\right) - A + C\overline{T}_\eta^*\right) = T_c = -10$$

where: $$\alpha_0 = \frac{\alpha_1+\alpha_2}{2} = 0.47$$

Budyko's Model

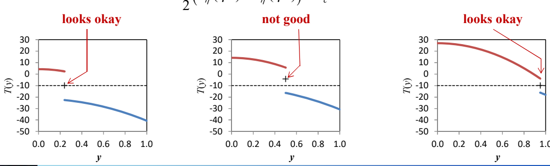
Ice Albedo Feedback

For each fixed η, there is a stable equilibrium solution for Budyko's equation.

Standard assumption: Permanent ice forms if the annual average temperature is below T_c=−10 °C and melts if the annual average temperature is above T_c.

Additional condition: The average temperature across the ice boundary is the critical temperature T_c.

$$\frac{1}{2}\left(T_\eta^*(\eta+) + T_\eta^*(\eta-)\right) = T_c = -10$$



Budyko's Model

Ice Albedo Feedback

$$R\frac{\partial T}{\partial t} = Qs(y)(1-\alpha(y,\eta)) - (A+BT) + C(\overline{T}-T)$$

Ice line condition: $$\frac{1}{B+C}\left(Qs(\eta)\left(1-\alpha_0\right) - A + C\overline{T}_\eta^*\right) = T_c = -10$$

Rewrite: $$h(\eta) = \frac{1}{B+C}\left(Qs(\eta)\left(1-\alpha_0\right) - A + C\overline{T}_\eta^*\right) - T_c = 0$$

Recall equilibrium GMT: $$\overline{T}_\eta^* = \frac{1}{B}\left(Q\left(1-\overline{\alpha}(\eta)\right) - A\right)$$

Recall average albedo: $$\overline{\alpha}(\eta) = \int_0^1 \alpha(y,\eta)s(y)dy = \alpha_2 - (\alpha_2-\alpha_1)S(\eta) = 0.62 - 0.3S(\eta)$$

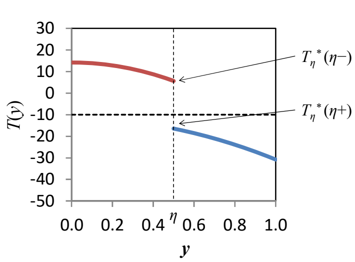
where: $$S(\eta) = \int_0^\eta s(y)dy = \eta - 0.241\left(\eta^3 - \eta\right)$$

$$h(\eta) \equiv \frac{Q}{B+C}\left(s(\eta)\left(1-\alpha_0\right) + \frac{C}{B}\left(1-\alpha_2+\left(\alpha_2-\alpha_1\right)S(\eta)\right)\right) - \frac{A}{B} - T_c = 0$$

Budyko's Model

Ice Albedo Feedback

ice line condition: $$\frac{1}{2}\left(T_\eta^*(\eta+) + T_\eta^*(\eta-)\right) = T_c = -10$$



Budyko's Model

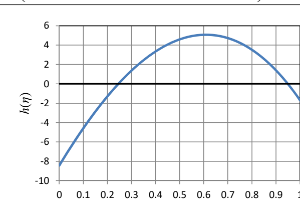
Ice Albedo Feedback

$$R\frac{\partial T}{\partial t} = Qs(y)(1-\alpha(y,\eta)) - (A+BT) + C(\overline{T}-T)$$

The additional condition: $$\frac{1}{2}\left(T_\eta^*(\eta+) + T_\eta^*(\eta-)\right) = T_c = -10$$

can be written: $$h(\eta) \equiv \frac{Q}{B+C}\left(s(\eta)\left(1-\alpha_0\right) + \frac{C}{B}\left(1-\alpha_2+\left(\alpha_2-\alpha_1\right)S(\eta)\right)\right) - \frac{A}{B} - T_c = 0$$

Two equilibria (zeros of h) satisfy the additional condition.



Budyko's Model

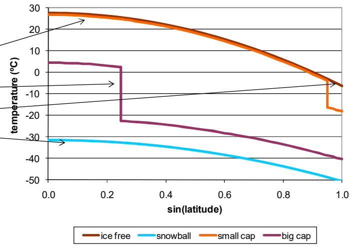
Ice Albedo Feedback

Equilibrium temperature profiles

$$T_\eta^*(y)=\frac{1}{B+C}\left(Qs(y)\left(1-\alpha(y,\eta)\right)-A+C\overline{T}_\eta^*\right)$$

Interesting Solutions:

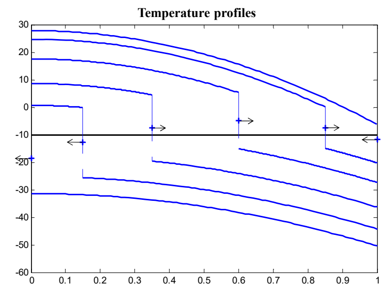
- small cap
- large cap
- ice free
- snowball



Budyko's Model

Budyko-Widiasih Model

$$\frac{d\eta}{dt}=\varepsilon h(\eta)$$



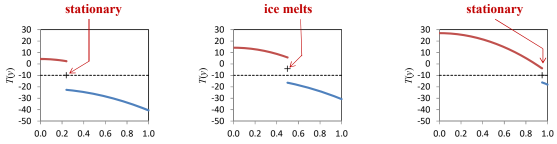
Budyko's Model

Dynamics of the Ice Line

$$R\frac{\partial T}{\partial t}=Qs(y)(1-\alpha(y,\eta))-(A+BT)+C(\overline{T}-T)$$

Idea:

If the average temperature across the ice line is above the critical temperature, some ice will melt, moving the ice line toward the pole. If it is below the critical temperature, the ice will advance toward the equator.



Widiasih's equation: $\frac{d\eta}{dt}=\varepsilon\left(T(\eta)-T_c\right)$

Budyko's Model

Summary

surface temperature — heat capacity — insolation — sin(latitude) — albedo — OLR — heat transport — $\overline{T}=\int_0^1 T(y)dy$

$$R\frac{\partial T}{\partial t}=Qs(y)(1-\alpha(y))-(A+BT)+C(\overline{T}-T)$$

reduces to

$$\frac{d\eta}{dt}=\varepsilon h(\eta)$$

$$\frac{d\eta}{dt}=\varepsilon h(\eta)=\varepsilon\left(\frac{Q}{B+C}\left(s(\eta)(1-\alpha_0)+\frac{C}{B}\left(1-\alpha_2+(\alpha_2-\alpha_1)S(\eta)\right)\right)-\frac{A}{B}-T_c\right)$$

Budyko's Model

Dynamics of the Ice Line

$$\frac{d\eta}{dt}=\varepsilon\left(T(\eta)-T_c\right)$$

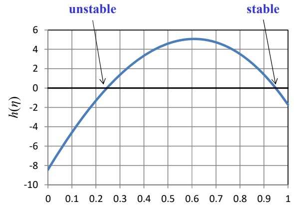
$$R\frac{\partial T}{\partial t}=Qs(y)(1-\alpha(y,\eta))-(A+BT)+C(\overline{T}-T)$$

State space: $[0,1]\times X$

Widiasih's Theorem. For sufficiently small ε, the system has an attracting invariant curve given by the graph of a function $\Phi_\varepsilon:[0,1]\to X$. On this curve, the dynamics are approximated by the equation

$$\frac{d\eta}{dt}=\varepsilon h(\eta)$$

experts only



Esther R. Widiasih, Dynamics of the Budyko Energy Balance Model, *SIAM J. Appl. Dyn. Syst.*, 12(4), 2068–2092.

Budyko's Model

Budyko-Widiasih Model

surface temperature — heat capacity — insolation — sin(latitude) — albedo — OLR — heat transport — $\overline{T}=\int_0^1 T(y)dy$

$$R\frac{\partial T}{\partial t}=Qs(y)(1-\alpha(y))-(A+BT)+C(\overline{T}-T)$$

What about the greenhouse effect?

$A+BT$ is the outgoing long wave radiation. This term decreases if the greenhouse gases increase. We view A as a parameter.

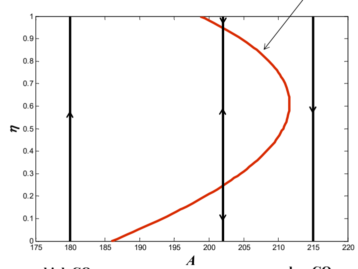
$$\frac{d\eta}{dt}=\varepsilon h(\eta,A)$$

Budyko's Model

Budyko-Widiasih Model

$$\frac{d\eta}{dt} = \varepsilon h(\eta, A)$$

isocline $h(\eta, A) = 0$



high CO_2 low CO_2

Snowball Earth

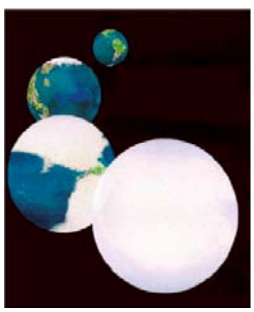
The continents were clustered near the equator.

Hoffman & Schrag, *Snowball Earth*, SCIENTIFIC AMERICAN, January 2000, 68-75

Snowball Earth

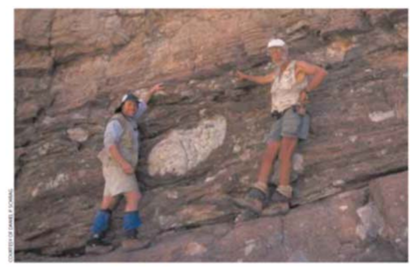
Is it possible for Earth to become completely covered in ice? (**Snowball Earth**)

Did it ever happen?



http://www.astrobio.net/topic/solar-system/earth/new-information-about-snowball-earth-period/

Snowball Earth

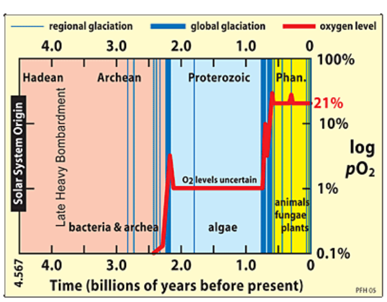


"Ice-rafted debris" occurred in ocean sediments near the equator, indicating large equatorial glaciers calving icebergs.

Hoffman & Schrag, *Snowball Earth*, SCIENTIFIC AMERICAN, January 2000, 68-75

Snowball Earth

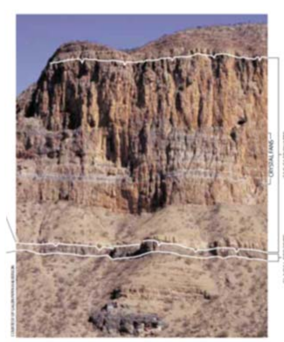
There is evidence that Snowball Earth has occurred, the last time about 600 million years ago.



http://www.snowballearth.org/when.html

Snowball Earth

Large limestone deposits "cap carbonates" are found immediately above the glacial debris, indicating a rapid warming period following the snowball.



Hoffman & Schrag, *Snowball Earth*, SCIENTIFIC AMERICAN, January 2000, 68-75

Snowball Earth

Idea:

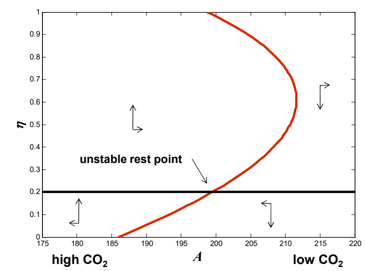
When the Earth is mostly ice-covered, silicate weathering slows down, but volcanic activity stays the same, allowing for a build-up of CO2 in the atmosphere.

When the Earth is mostly ice-free, silicate weathering speeds up, drawing down the CO2 in the atmosphere.

Budyko's Model

Budyko-Widiasih-Paleocarbon Model

$$\frac{d\eta}{dt} = \varepsilon h(\eta, A), \quad \frac{dA}{dt} = \tilde{\varepsilon}(\eta - \eta_c)$$



Budyko's Model

Budyko-Widiasih Model

$$\frac{d\eta}{dt} = \varepsilon h(\eta, A)$$

What if A is a dynamical variable?

Simple equation:

$$\frac{dA}{dt} = \tilde{\varepsilon}(\eta - \eta_c)$$

$$0 < \tilde{\varepsilon} \ll \varepsilon \ll 1$$

MCRN Paleocarbon equation (silicate weathering)

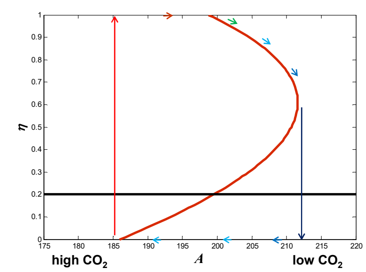
New system:

$$\boxed{\begin{aligned} \frac{dA}{dt} &= \tilde{\varepsilon}(\eta - \eta_c) \\ \frac{d\eta}{dt} &= \varepsilon h(\eta, A) \end{aligned}}$$

Budyko's Model

Budyko-Widiasih-Paleocarbon Model

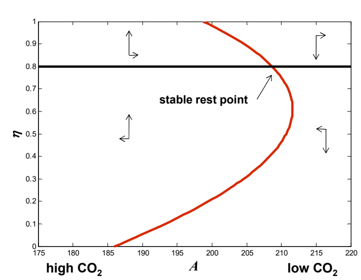
Snowball – Hothouse Oscillations



Budyko's Model

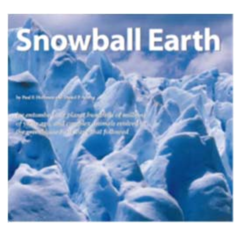
Budyko-Widiasih-Paleocarbon Model

$$\frac{d\eta}{dt} = \varepsilon h(\eta, A), \quad \frac{dA}{dt} = \tilde{\varepsilon}(\eta - \eta_c)$$

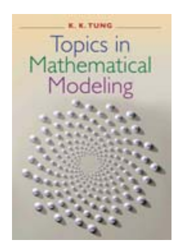


Budyko's Model

Suggested Reading



Hoffman & Schrag, *Snowball Earth*, SCIENTIFIC AMERICAN, January 2000, 68-75



K.K. Tung, *Topics in Mathematical Modeling*, PRINCETON UNIVERSITY PRESS, 2007, Chapter 8