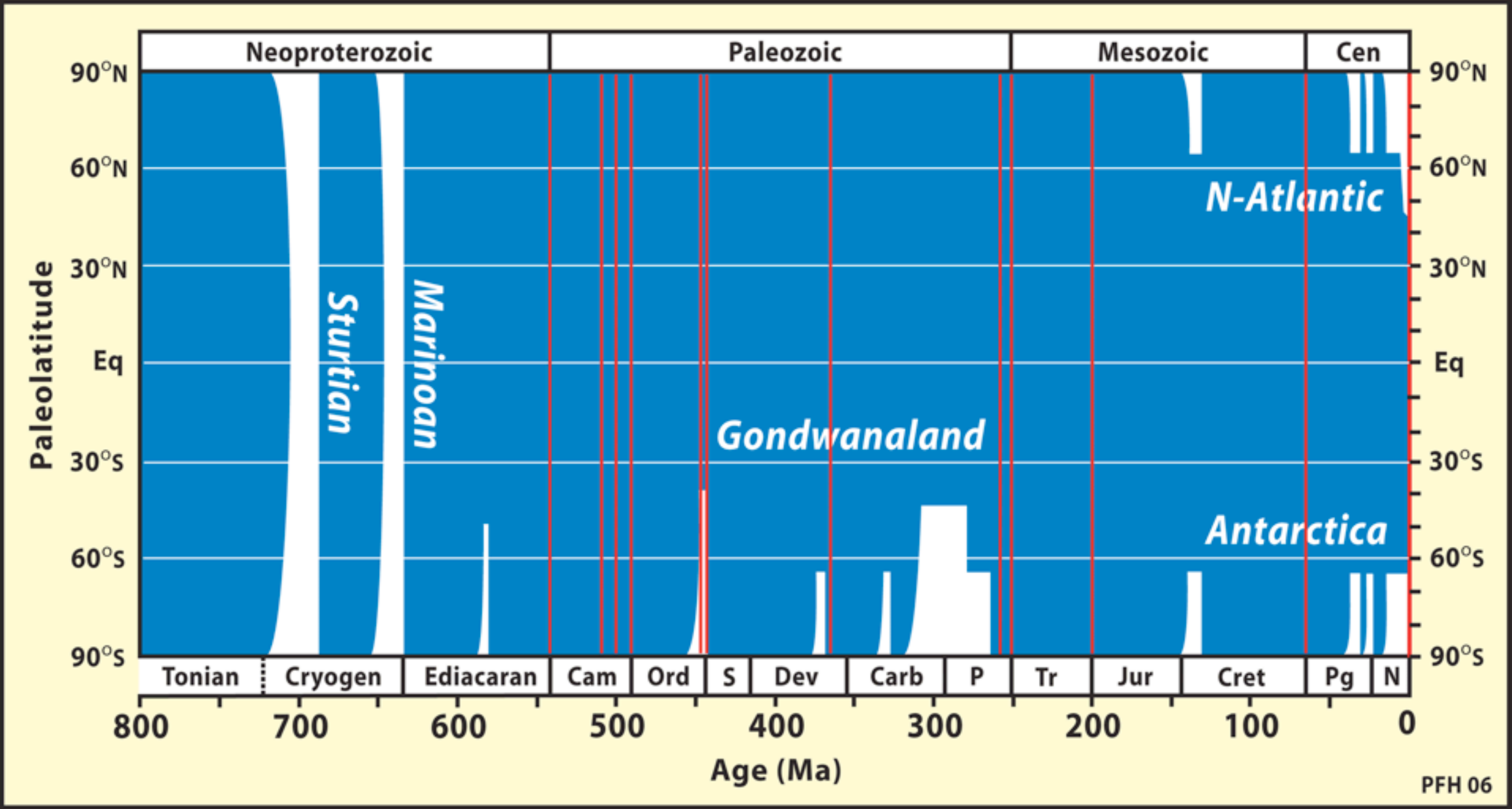
PHY392S
Physics of Climate

Lecture 20

Snowball Earth

From http://www.snowballearth.org/

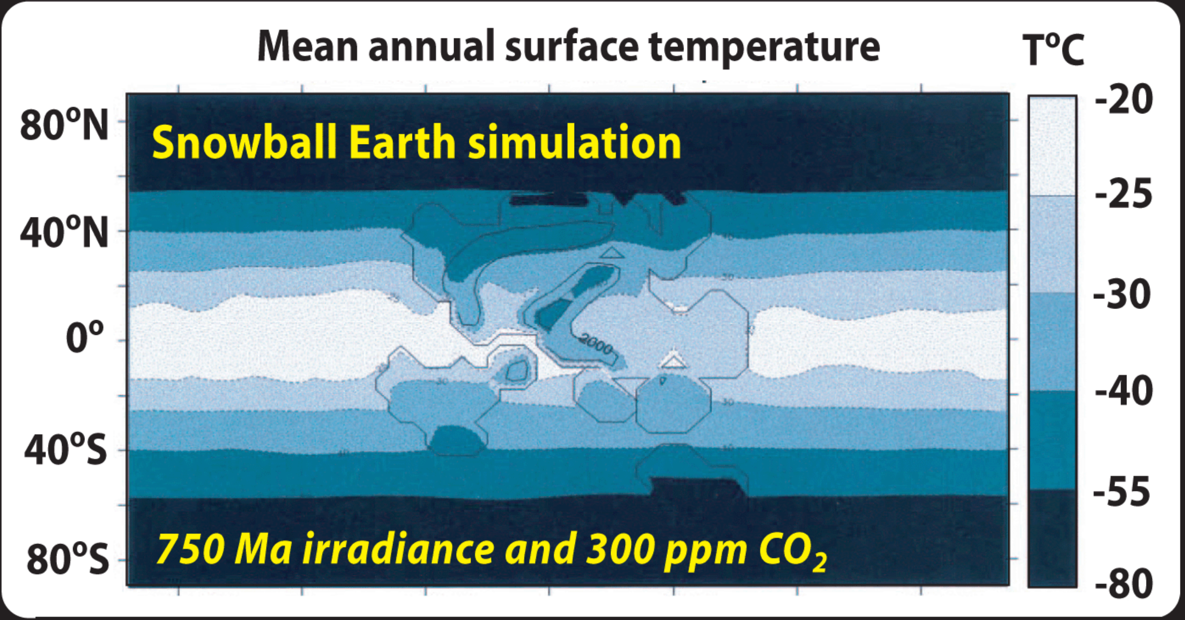
Paleogeographic extent of continental ice sheets and permanent sea ice over the last 800 Myr (red lines indicate major mass extinctions)



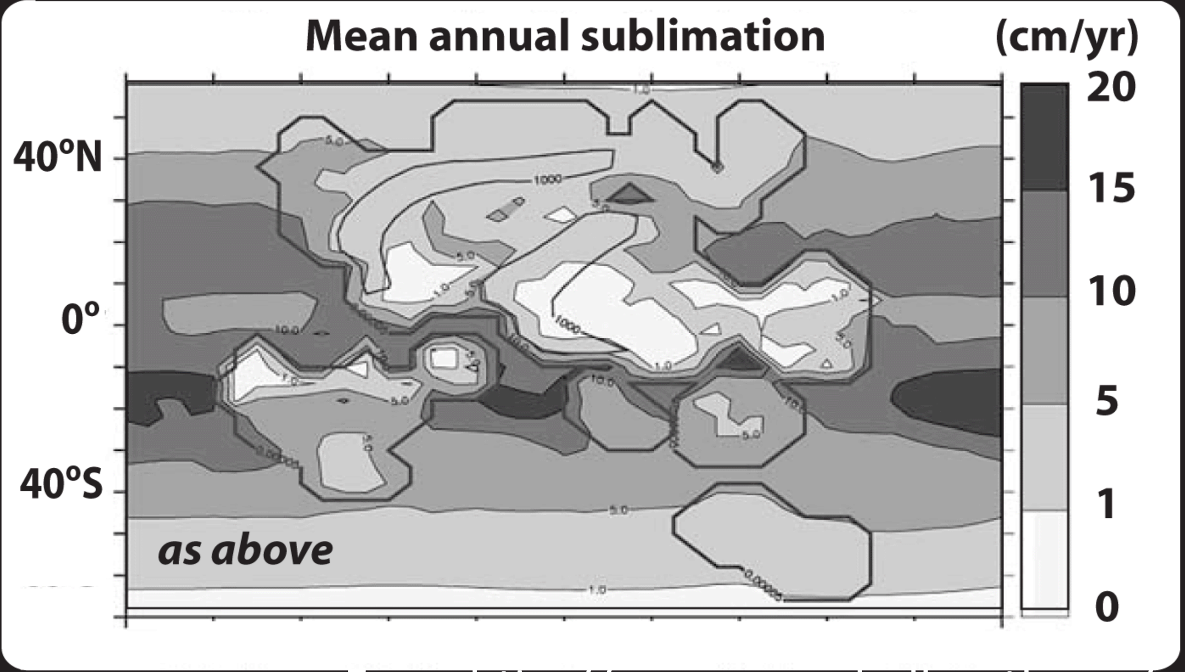
From http://www.snowballearth.org/

LMD - AGCM results

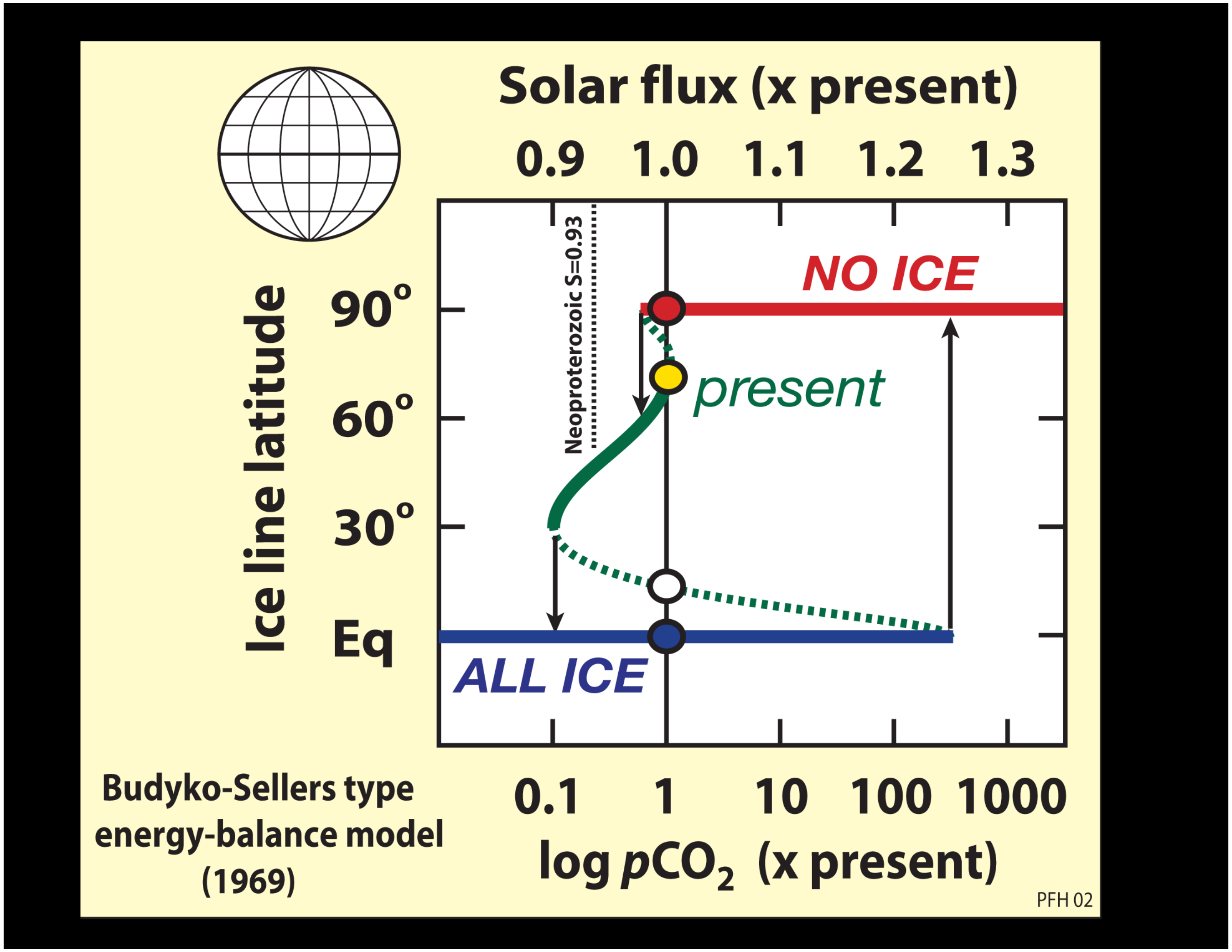
Donnadieu *et al.*, 2003, EPSL 208, p.101-112.



Note sublimation of subtropical sea ice, and resulting accumulation of snow in tropical and subtropical highlands.

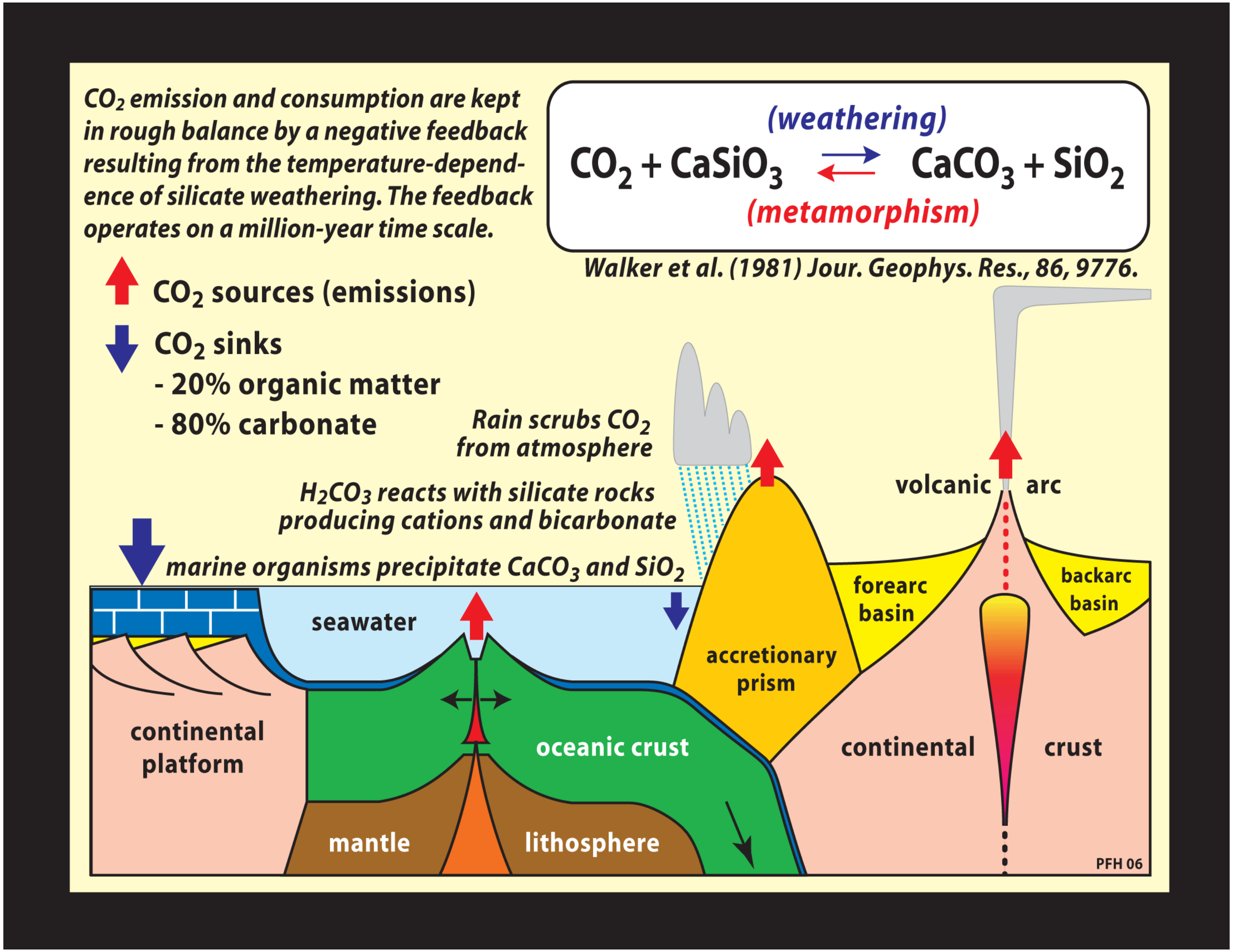


From http://www.snowballearth.org/

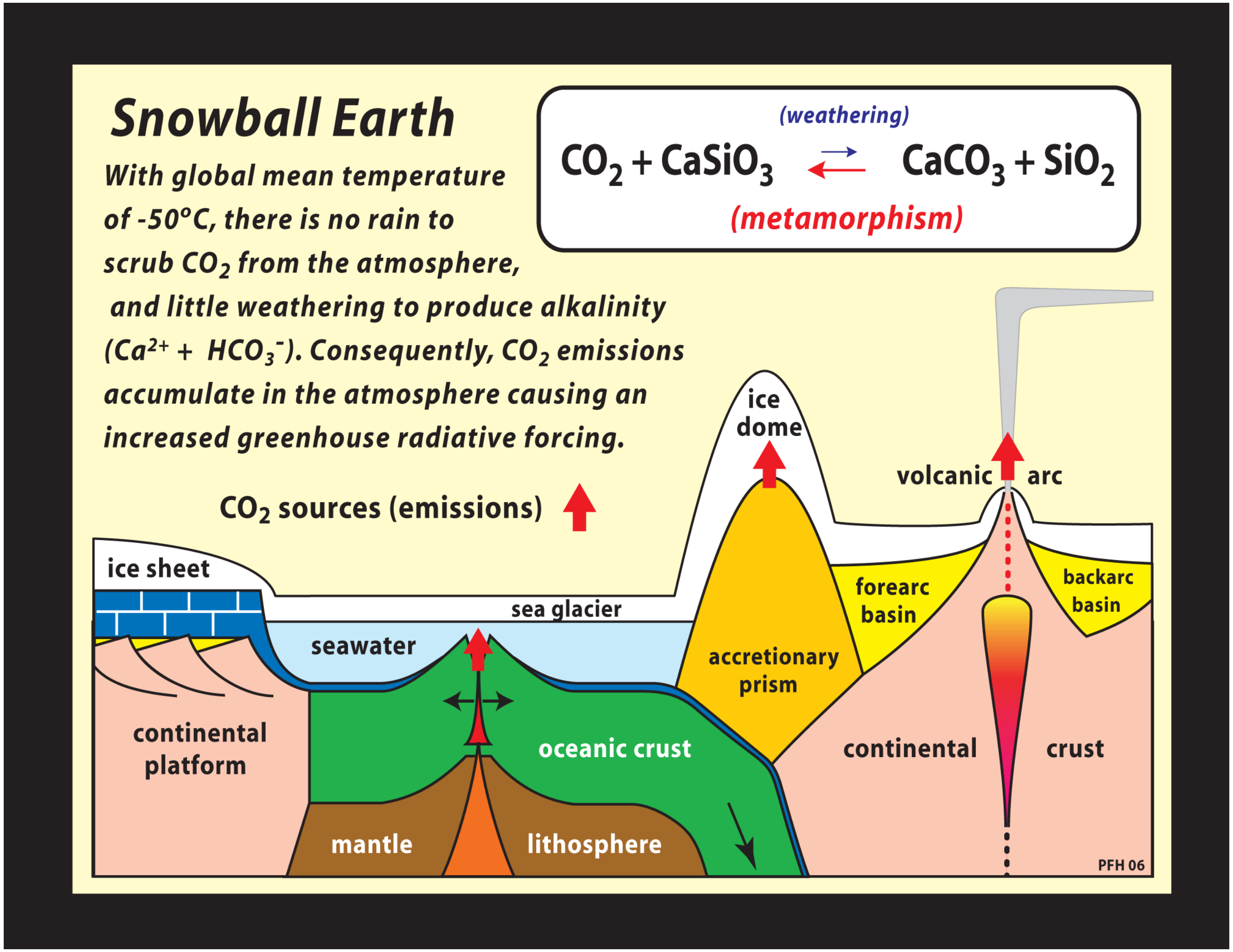


Under the present Solar flux (1.0), three stable climate states are possible, all ice (blue), no ice (red) and small ice (yellow). Large ice (open circle) is unstable and spontaneously falls to all ice

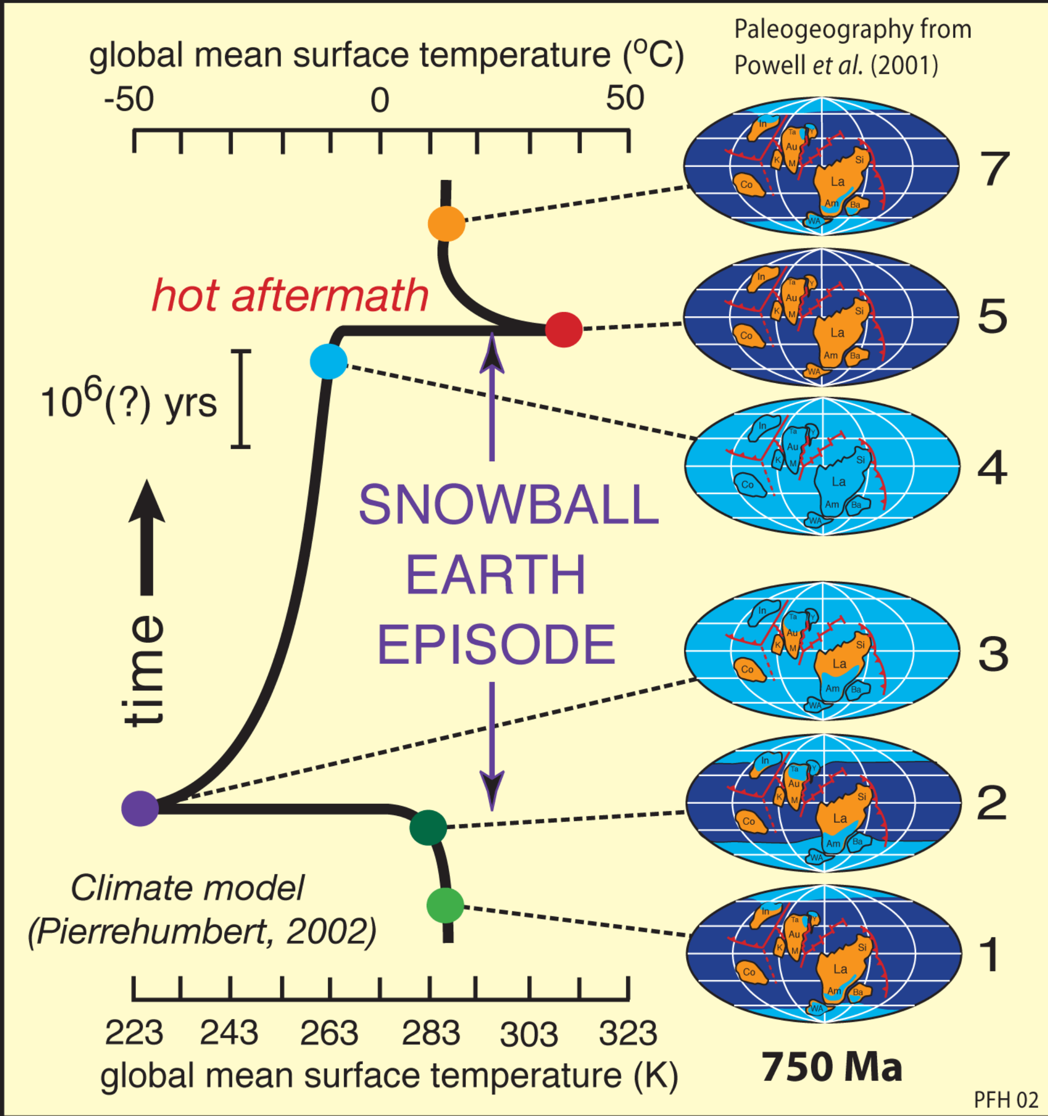
From http://www.snowballearth.org/



Silicate weathering represents a sink of atmospheric CO_2



Under snowball Earth conditions, silicate weathering is suppressed, allowing CO_2 (from outgassing from volcanic activity) to build up in the atmosphere.


global mean surface temperature (°C)
-50
0
50
Paleogeography from
Powell et al. (2001)
7
5
4
3
2
1
hot aftermath
10^6(?) yrs
time
SNOWBALL
EARTH
EPISODE
Climate model
(Pierrehumbert, 2002)
223
243
263
283
303
323
global mean surface temperature (K)
750 Ma
PFH 02

Ice Albedo Feedback

The effect of solar radiation variations on the climate of the Earth

By M. I. BUDYKO, *Main Geophysical Observatory, Leningrad, M. Spasskaja 7*

(Manuscript received September 25, 1968, revised version December 18, 1968)

ABSTRACT

It follows from the analysis of observation data that the secular variation of the mean temperature of the Earth can be explained by the variation of short-wave radiation, arriving at the surface of the Earth. In connection with this, the influence of long-term changes of radiation, caused by variations of atmospheric transparency on the thermal regime is being studied. Taking into account the influence of changes of planetary albedo of the Earth under the development of glaciations on the thermal regime, it is found that comparatively small variations of atmospheric transparency could be sufficient for the development of quaternary glaciations.

Budyko's Model

$$I = a + BT - (a_1 + B_1T)n$$

I = outgoing radiation (in Kcal/cm_2 per month)
T = temperature at the surface (°C)
n = cloudiness in fractions of unit

Heat balance of the Earth Atmosphere system: $Q(1-\alpha) - I = A$

Q = solar radiation incident at TOA
α = albedo
A = gain or loss of heat as a result of meridional transport in the atmosphere and oceans

For the whole planet: $A = 0$

$$Q_p(1-\alpha_p) = I$$

$$T_p = \frac{Q(1-\alpha_p) - a + a_1 n}{B - B_1 n}$$

Budyko's Model

Assume that the meridional transport can be parameterized as a relaxation in temperature at each latitude back to the global mean:

$$A = \beta(T - T_p)$$ where β = 0.235 kcal/cm^2 month degree

$$I = Q(1-\alpha) - \beta(T - T_p)$$

and

$$I = a + BT - (a_1 + B_1 T)n$$

$$T = \frac{Q(1-\alpha) - a + a_1 n + \beta T_p}{\beta + B - B_1 n}$$

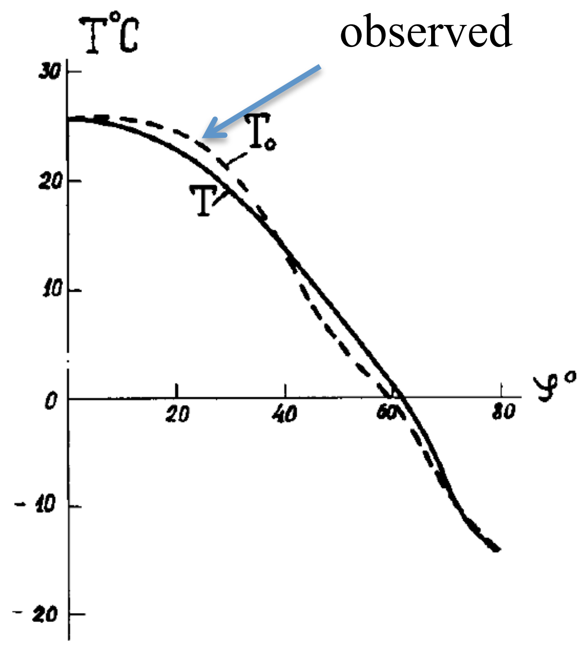


Fig. 3. The average latitudinal temperature distribution.

Budyko's Model

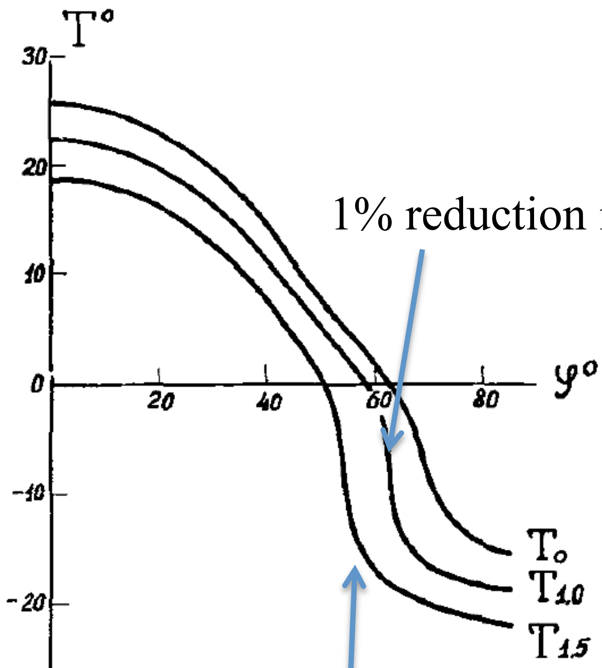
Albedo variation

Latitude	Albedo
80°	0.62
70°	0.50
0-60°	0.32

Southern boundary of existing sea ice = 72°. If a decrease in solar radiation results in an equatorward expansion of ice (to latitudes less than 72°, then the albedo becomes 0.62 at these latitudes and 0.50 at the southern ice boundary

$$T = \frac{Q(1-\alpha) - a + a_1 n + \beta T_p' + \dfrac{\beta Q_p}{B - B_1 n}\left[\dfrac{\Delta Q_p}{Q_p}(1-\alpha_p - 0.30S) - 0.30S\right]}{\beta + B - B_1 n}$$

Budyko's Model



1% reduction in radiation

Fig. 4. The dependence of temperature distribution on radiation amount.

1.5% reduction in radiation

Mean Temp of planet and latitudinal extent of glaciation

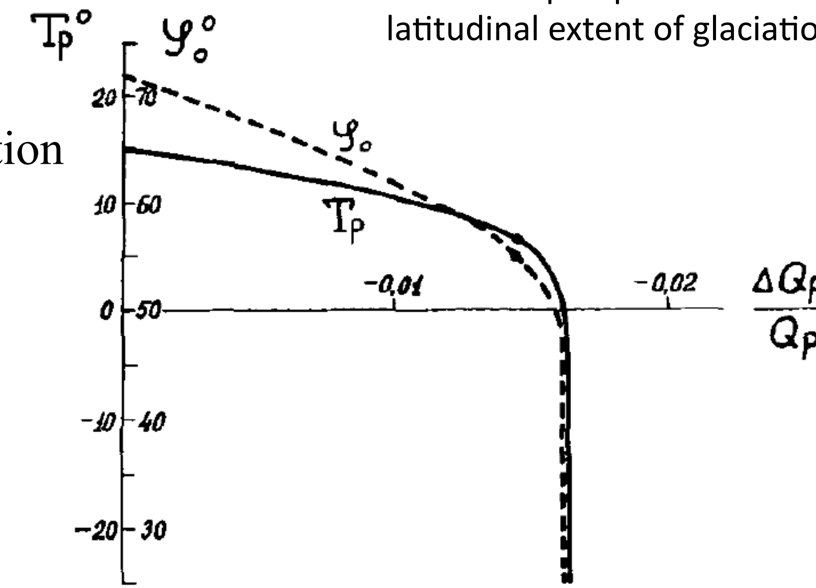


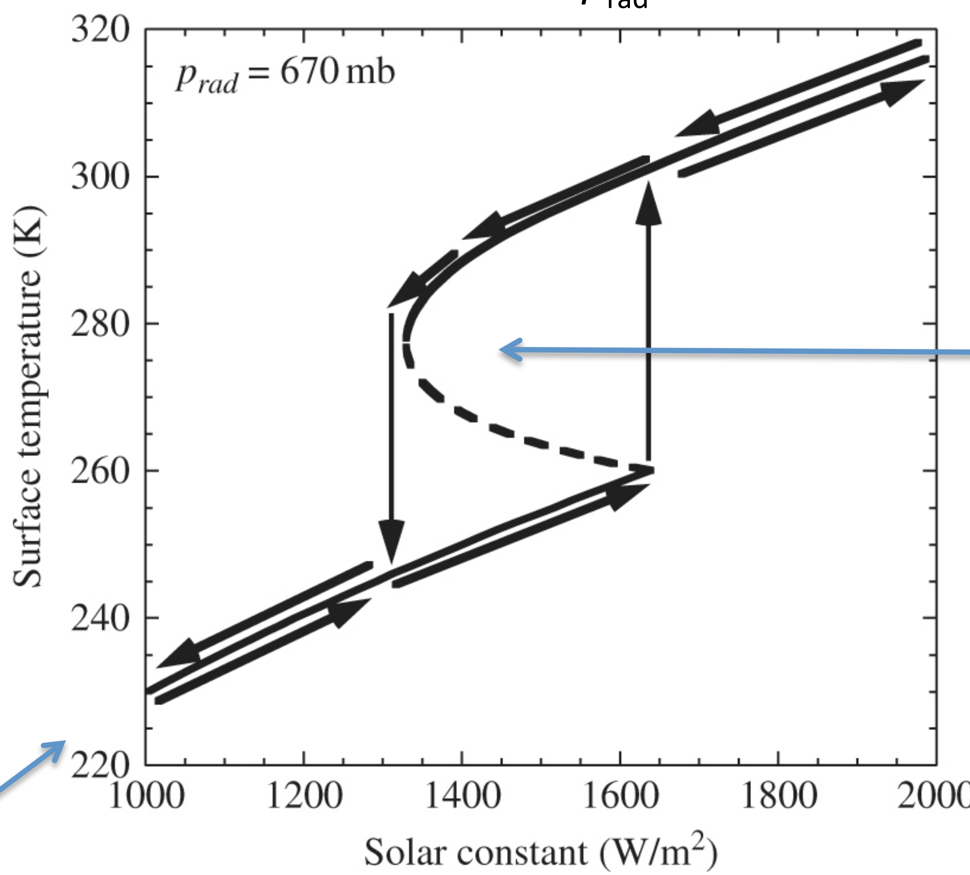
Fig. 5. The dependence of the Earth's temperature and ice cover boundary on radiation variations.

At 1.6% reduction, ice line at 50° and shifts to lower latitudes

Snowball Earth and Hysteresis

Varying the solar constant with p_{rad} fixed

With OLR from p_{rad} = 670 hPa



A warm or a cold state is possible, depending on the history of the state.

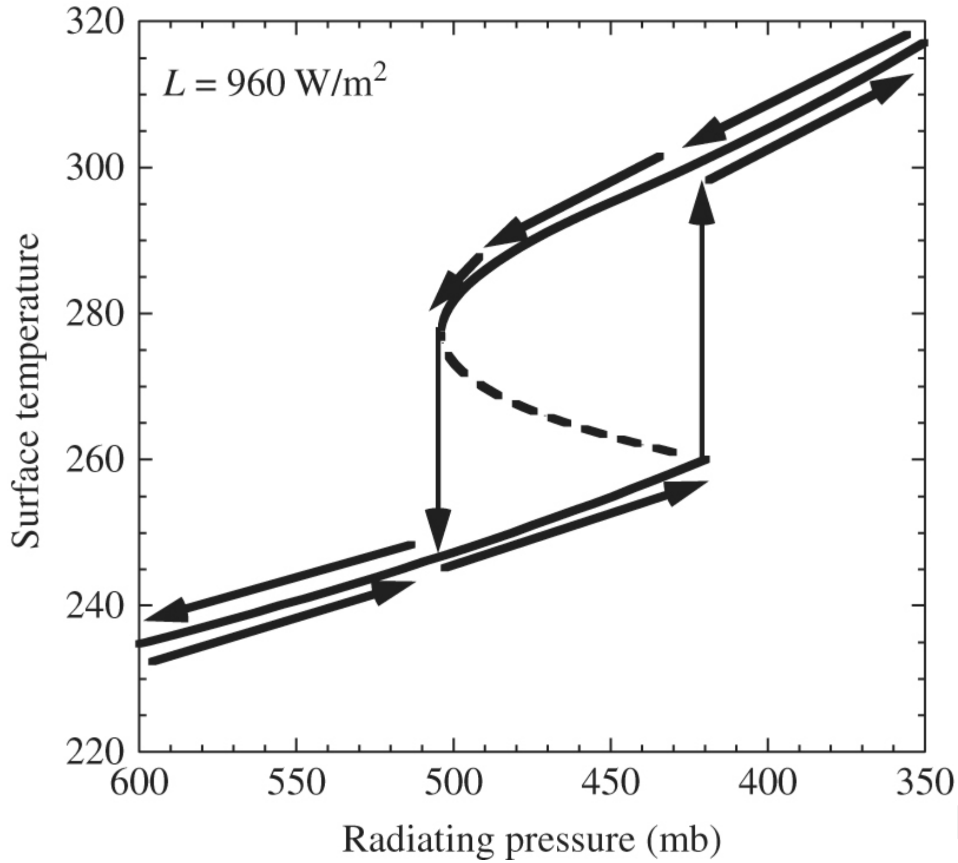
Snowball Earth conditions

[Pierrehumbert, 2010]

Snowball Earth and Hysteresis

Varying p_{rad} with the solar constant fixed

With Solar Constant = 960W/m^2



[Pierrehumbert, 2010]

For the current solar constant, the hysteresis loop is between 690-570 hPa

The Initiation of Modern "Soft Snowball" and "Hard Snowball" Climates in CCSM3. Part I: The Influences of Solar Luminosity, CO_2 Concentration, and the Sea Ice/Snow Albedo Parameterization

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(Manuscript received 5 April 2011, in final form 6 September 2011)

ABSTRACT

The "Snowball Earth" hypothesis, proposed to explain the Neoproterozoic glacial episodes in the period 750–580 million years ago, suggested that the earth was globally covered by ice/snow during these events. This study addresses the problem of the forcings required for the earth to enter such a state of complete glaciation using the Community Climate System Model, version 3 (CCSM3). All of the simulations performed to address this issue employ the geography and topography of the present-day earth and are employed to explore the combination of factors consisting of total solar luminosity, CO_2 concentration, and sea ice/snow albedo parameterization that would be required for such an event to occur. The analyses demonstrate that the critical conditions beyond which runaway ice–albedo feedback will lead to global freezing include 1) a 10%–10.5% reduction in solar radiation with preindustrial greenhouse gas concentrations; 2) a 6% reduction in solar radiation with 17.5 ppmv CO_2; or 3) 6% less solar radiation and 286 ppmv CO_2 if sea ice albedo is equal to or greater than 0.60 with a snow albedo of 0.78, or if sea ice albedo is 0.58 with a snow albedo equal to or greater than 0.80. These bifurcation points are very sensitive to the sea ice and snow albedo parameterizations. Moreover, "soft Snowball" solutions are found in which tropical open water oceans stably coexist with year-round snow-covered low-latitude continents, implying that tropical continental ice sheets would actually be present. The authors conclude that a "soft Snowball" is entirely plausible, in which the global sea ice fraction may reach as high as 76% and sea ice margins may extend to 10°S(N) latitudes.

[Journal of Climate, 2012]

Modern “soft snowball” and “hard snowball” Climates

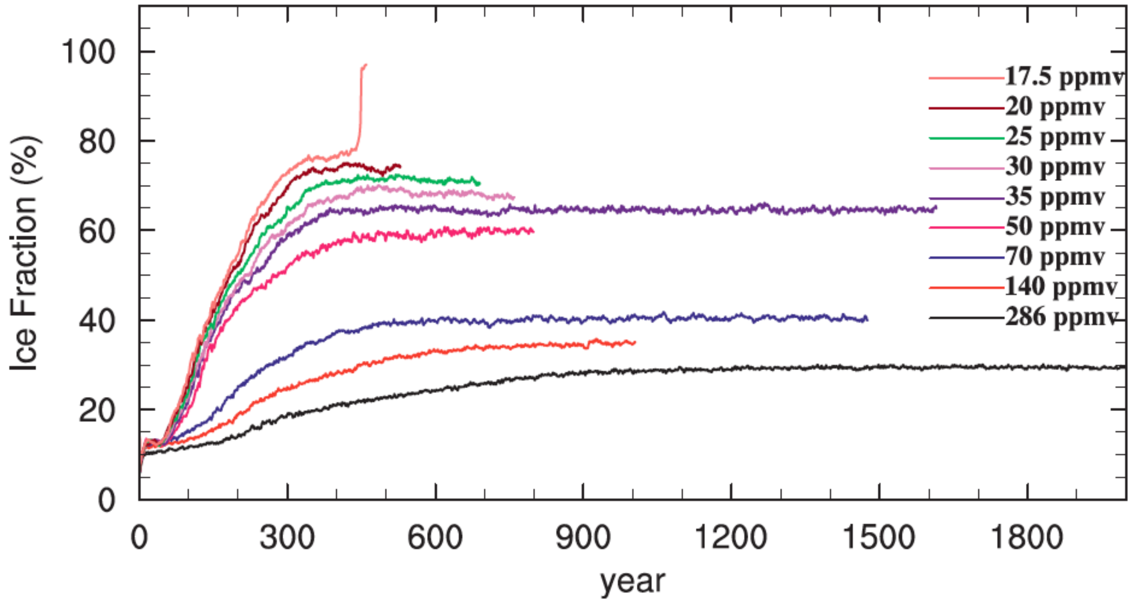

FIG. 3. Global- and annual-mean sea ice evolution in response to abrupt decreases of CO_2 concentration. Solar radiation is fixed at 94% of the present level. The sea ice (snow) albedo is 0.50 (0.78).

[Yang et al., 2012]

Modern "soft snowball" and "hard snowball" Climates

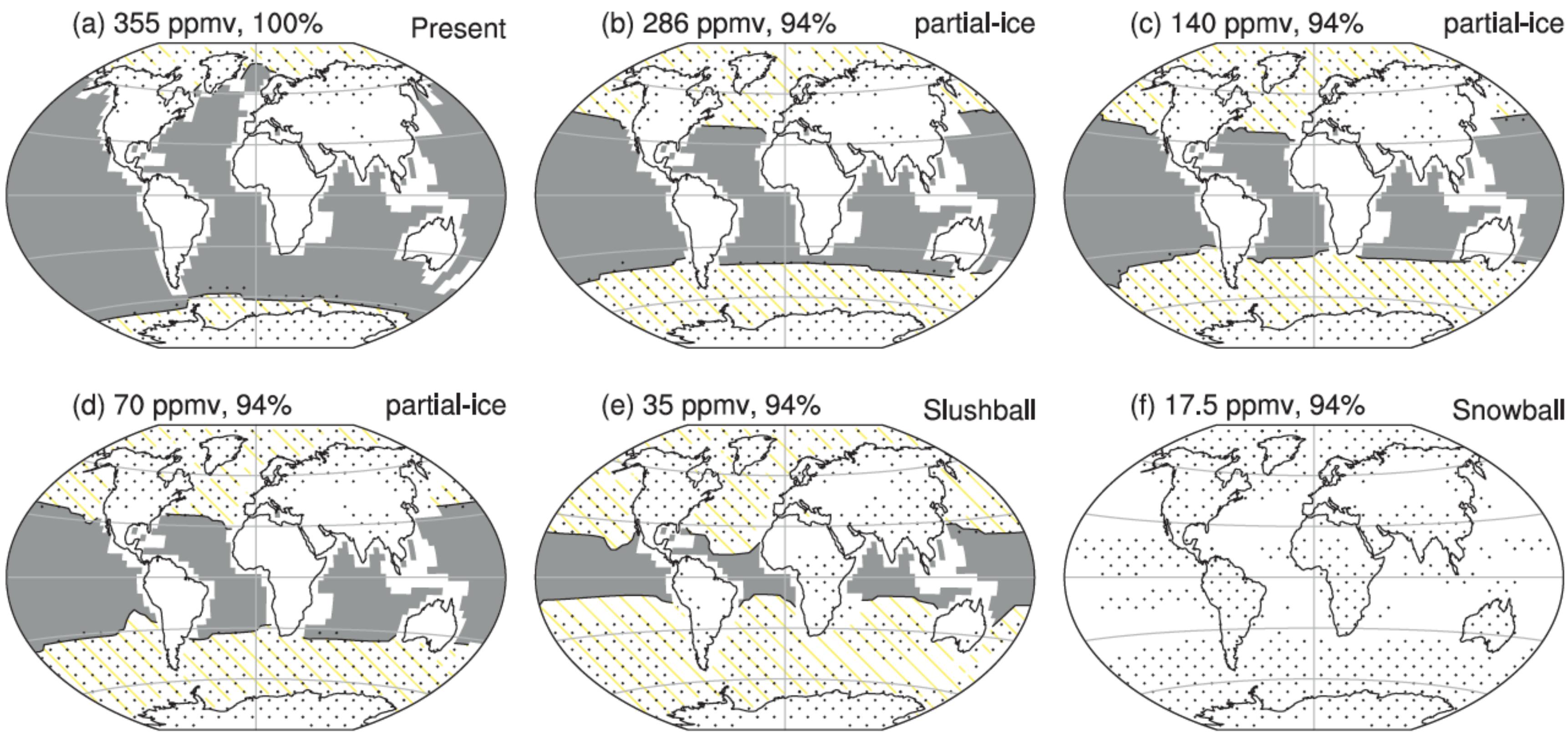

FIG. 5. Annual-mean sea ice (white), snow over sea ice and land (stippled, where snow depth is above 0.04-m liquid water equivalent) and ice-free ocean (gray) in the experiments with different solar radiations and CO_2 concentrations.

[Yang et al., 2012]

Modern "soft snowball" and "hard snowball" Climates

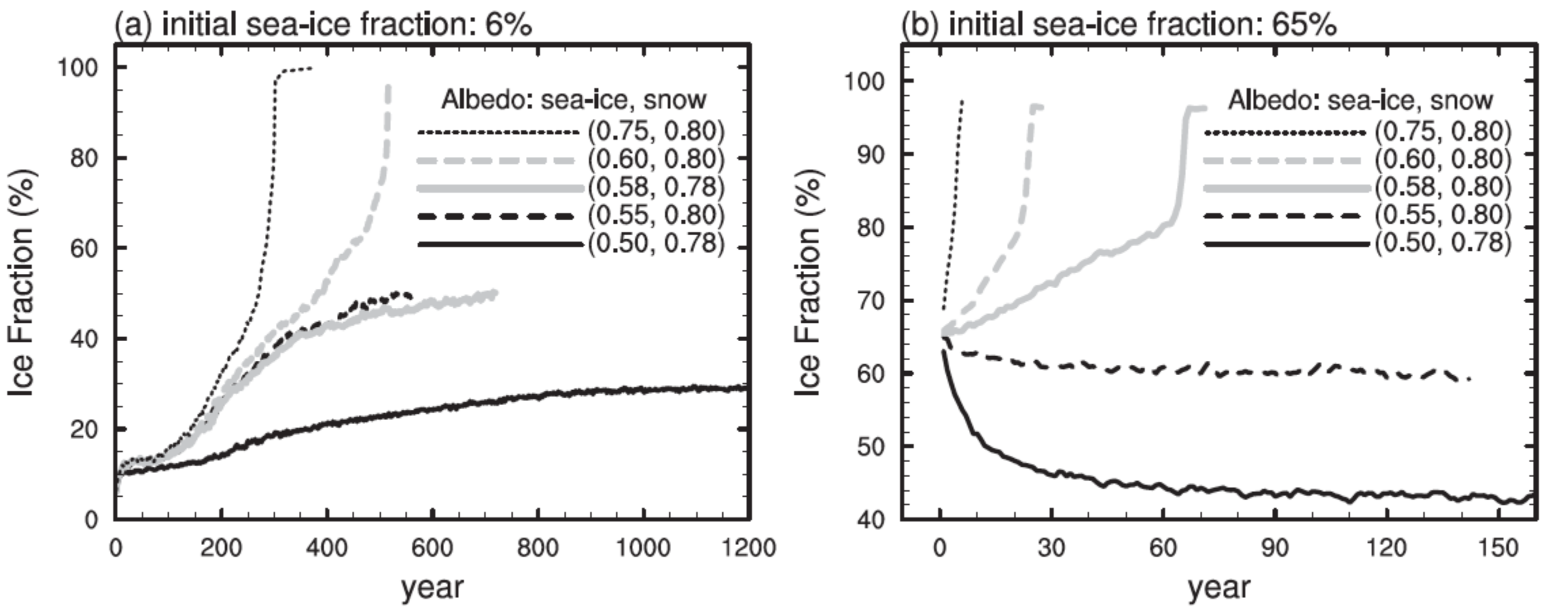

FIG. 10. Sea ice fraction as a function of sea ice/snow albedo: numbers in parentheses are sea ice and snow albedo, respectively. Initial sea ice fraction is (a) 6% and (b) 65%. Solar radiation is 94% of the present level, and CO_2 concentration is 286 ppmv.

[Yang et al., 2012]

The maximum stable sea ice coverage also depends on the sea ice/snow albedo