Arctic Sea Ice Loss: a Tipping Point in Earth's Climate?

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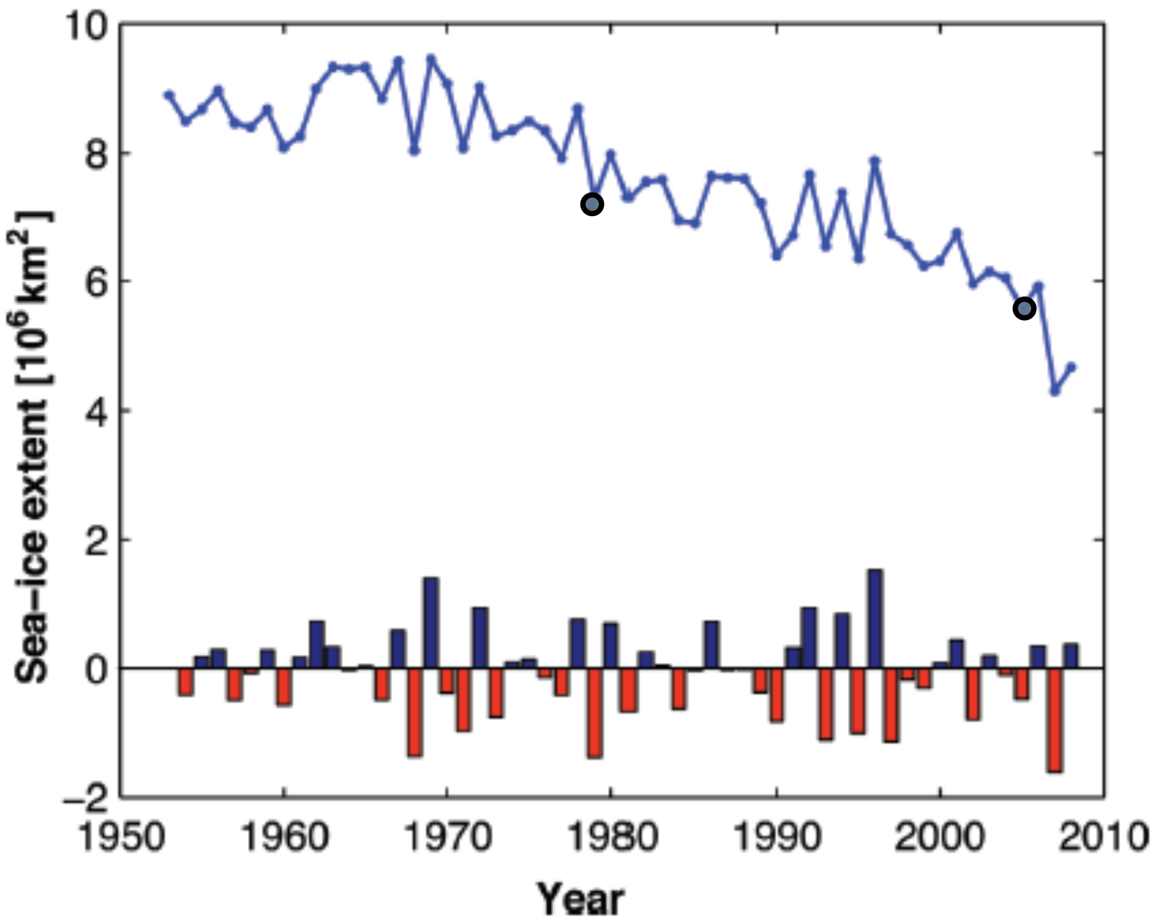
NSF funded "Mathematics and Climate Research Network"
http://www.mathclimate.org/

NASA Satellite Images

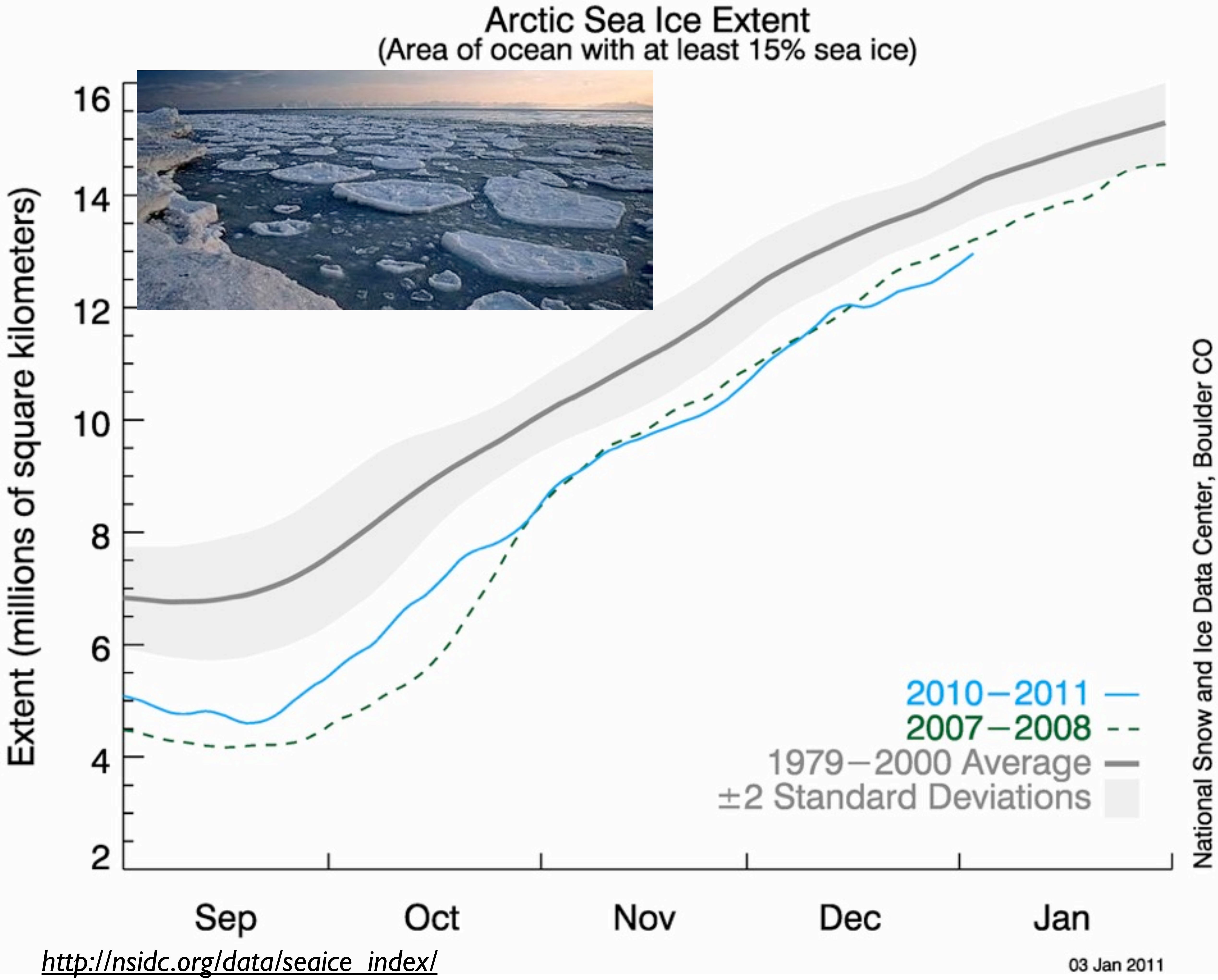
"Satellites See a Double-Texas Sized Loss In Arctic Sea Ice"

NASA **09.28.05**

Sea Ice Minimum 1979:

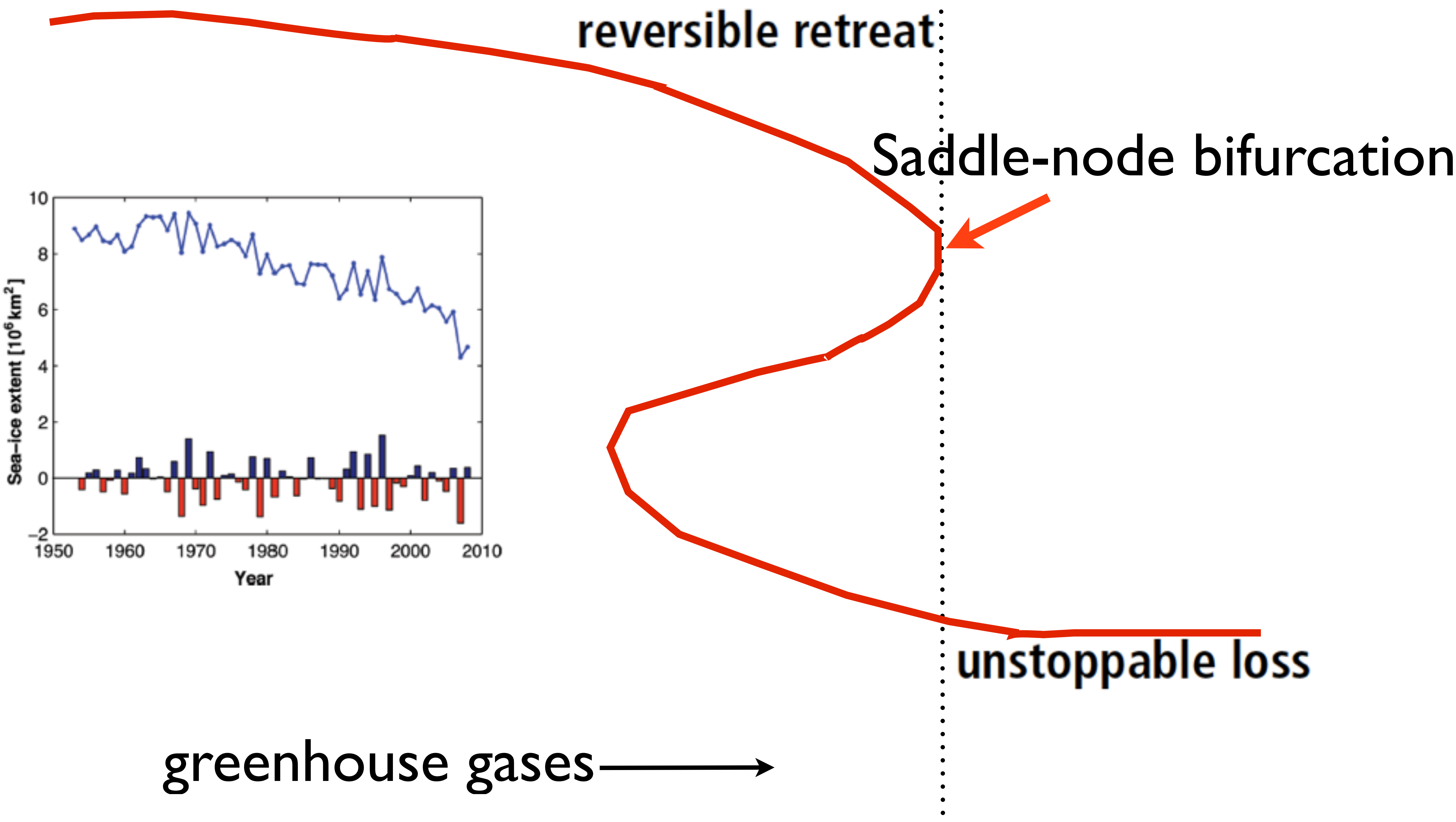


Sea Ice Minimum 2005:



http://nsidc.org/data/seaice_index/

Are there 'tipping points' for Arctic sea ice loss?



Significance?

Regional implications:

Arctic wildlife and ecology; Arctic indigenous peoples and their economy

Global political-economic implications:

natural energy reserves, opening the Northwest passage

Climate implications:

global climate feedbacks involving the Arctic region

"Sociological" implications:

Arctic amplification of climate change -- is it a canary in the coal mine?

Are there ‘tipping points’ for Arctic sea ice loss?

YES:

“... have led to a tipping point in the public perception
of the future melting of the Earth’s ice masses,
there still exists a significant lack of scientific understanding
of the cryospheric ‘tipping elements’.”

The future of ice sheets and sea ice: Between reversible retreat and unstoppable loss

Dirk Notz[1]

PNAS | December 8, 2009 | vol. 106 | no. 49 | 20595

Methods

Observations:

e.g. satellite images, field studies, proxy data for past climate reconstructions, etc.

Global Climate Models (GCMs):

e.g. state of the art codes that simulate everything at highest possible resolution, and considering different IPCC future emission scenarios.

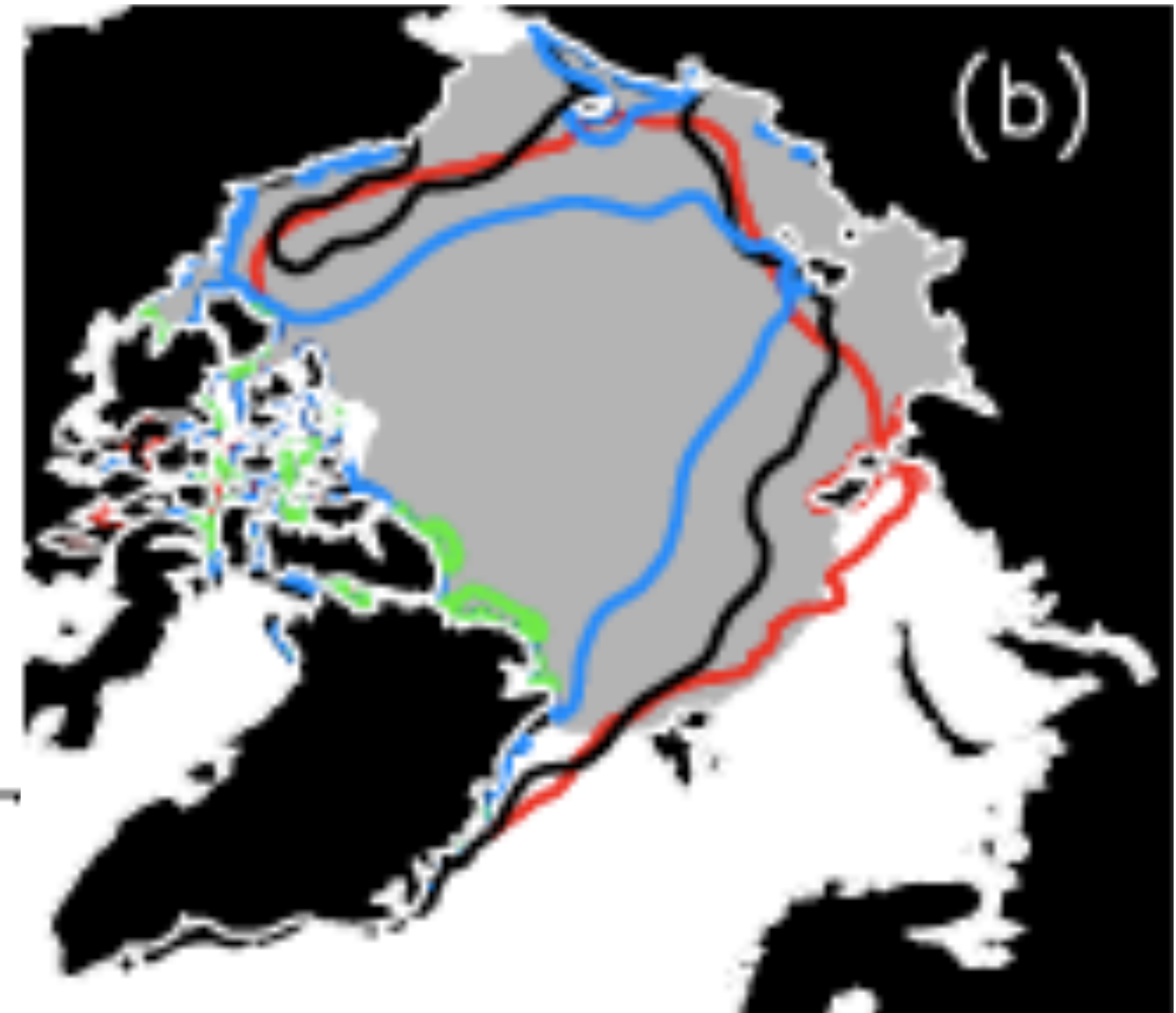
Intermediate Complexity Climate Models:

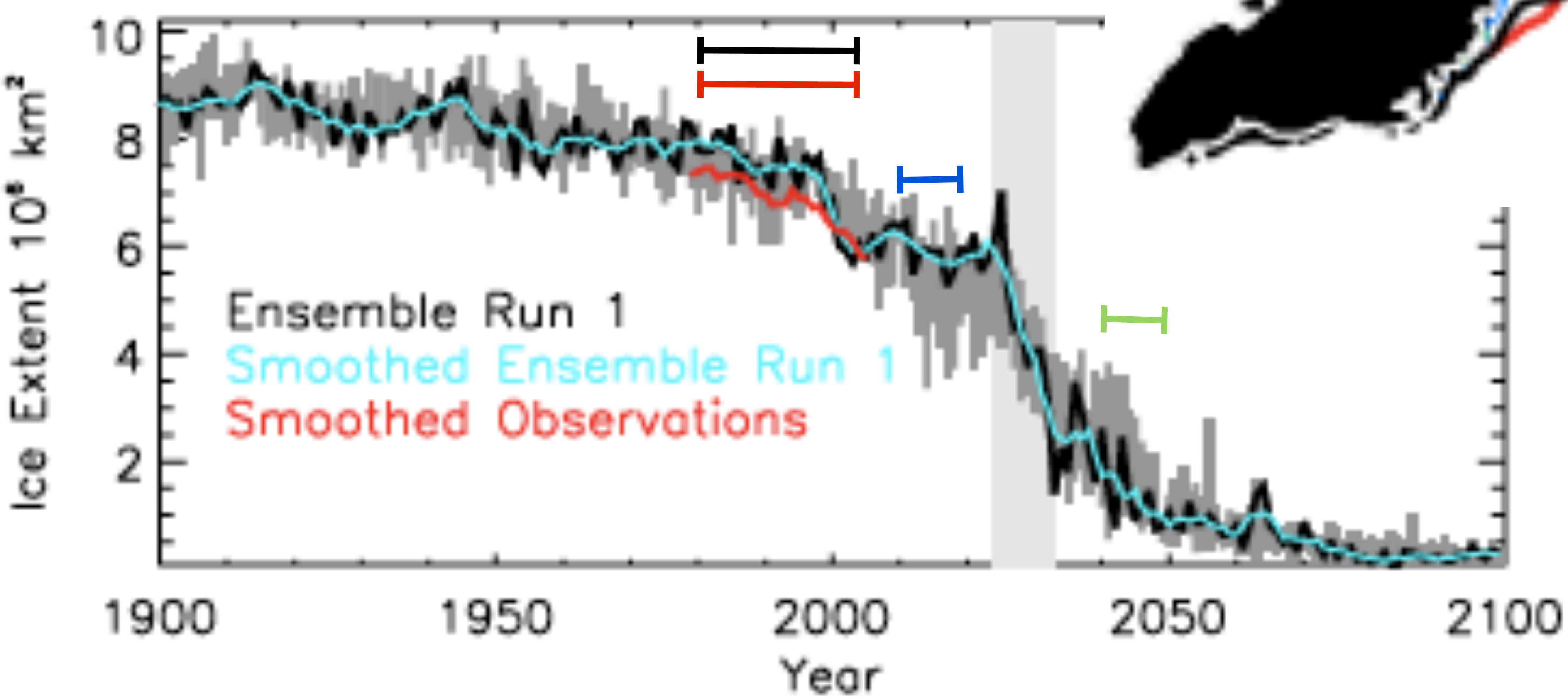
e.g. computational coupled earth system models that don't start from the primitive equations. Run much faster than GCMs, but contain more parameterizations.

Conceptual Models:

e.g. simple mathematical models with feedbacks, included or not, in some fashion.

Tipping points in GCMs?

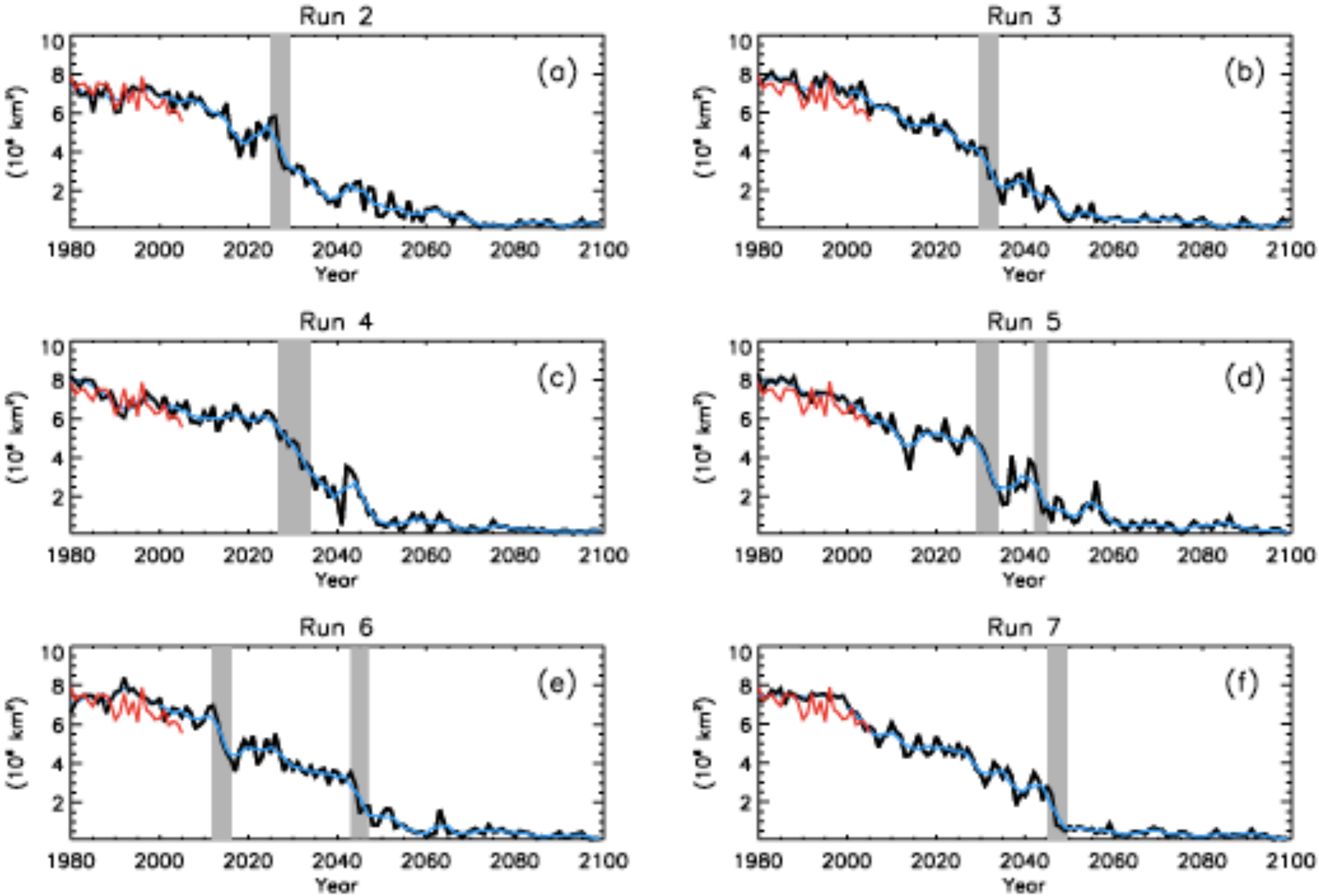




Holland, Bitz and Tremblay, GRL (2006)

Tipping points in GCMs?

HOLLAND ET AL.: ABRUPT REDUCTIONS IN ARCTIC SEA ICE



Conceptual Models

(a.k.a. Energy Balance Models, Box Models, Toy Models...)

some "classics":

Budyko 1969 / Sellers 1969 ← ice-albedo feedback

North 1984

Thorndike 1992

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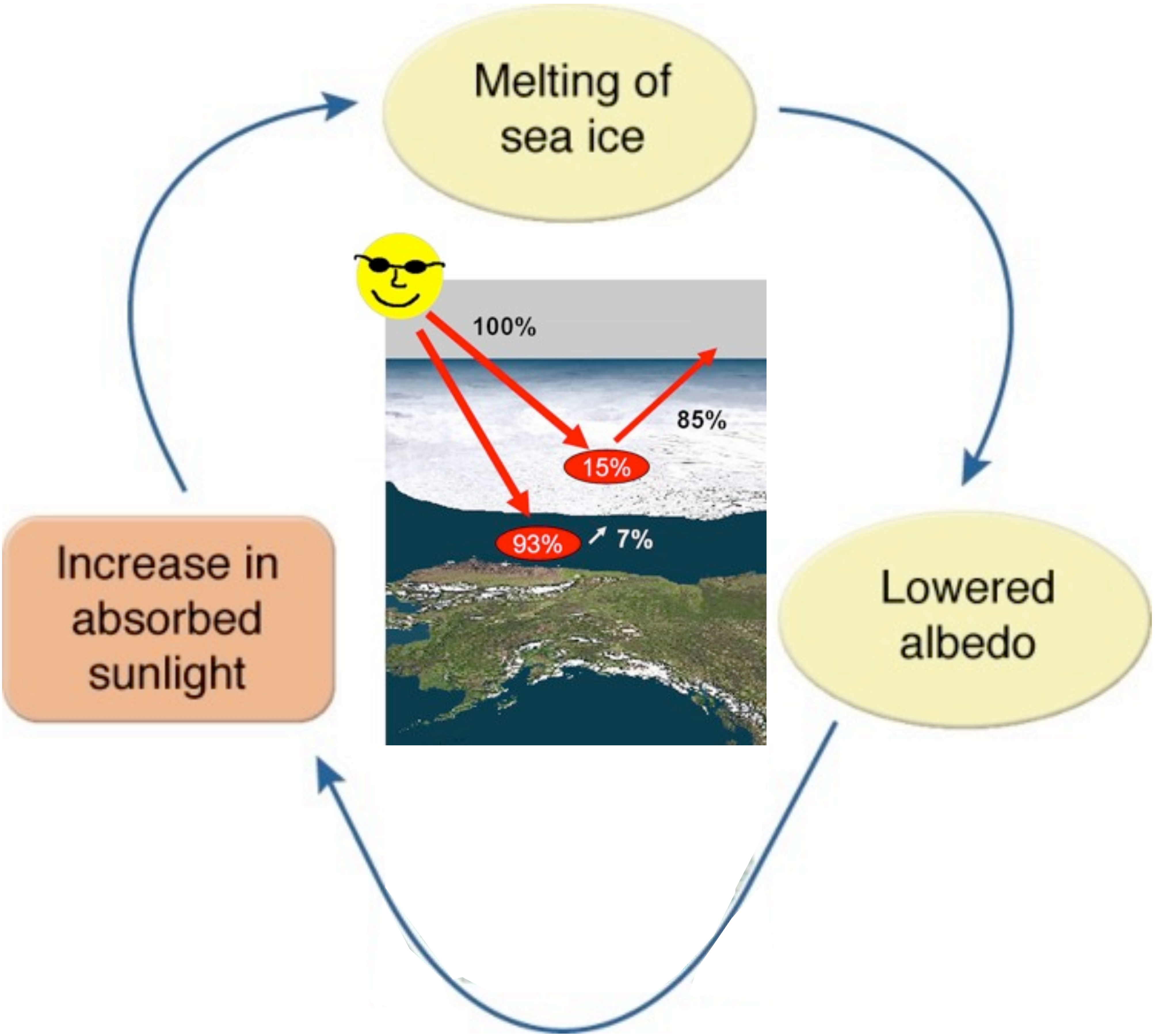
& more recently:

Merryfield, Holland & Monahan 2008

Eisenman & Wettlaufer 2009 ← +sea ice thermodynamics

ice-albedo feedback:



EW09 0-D model: positive ice-albedo feedback *vs.* stabilizing sea ice thermodynamics

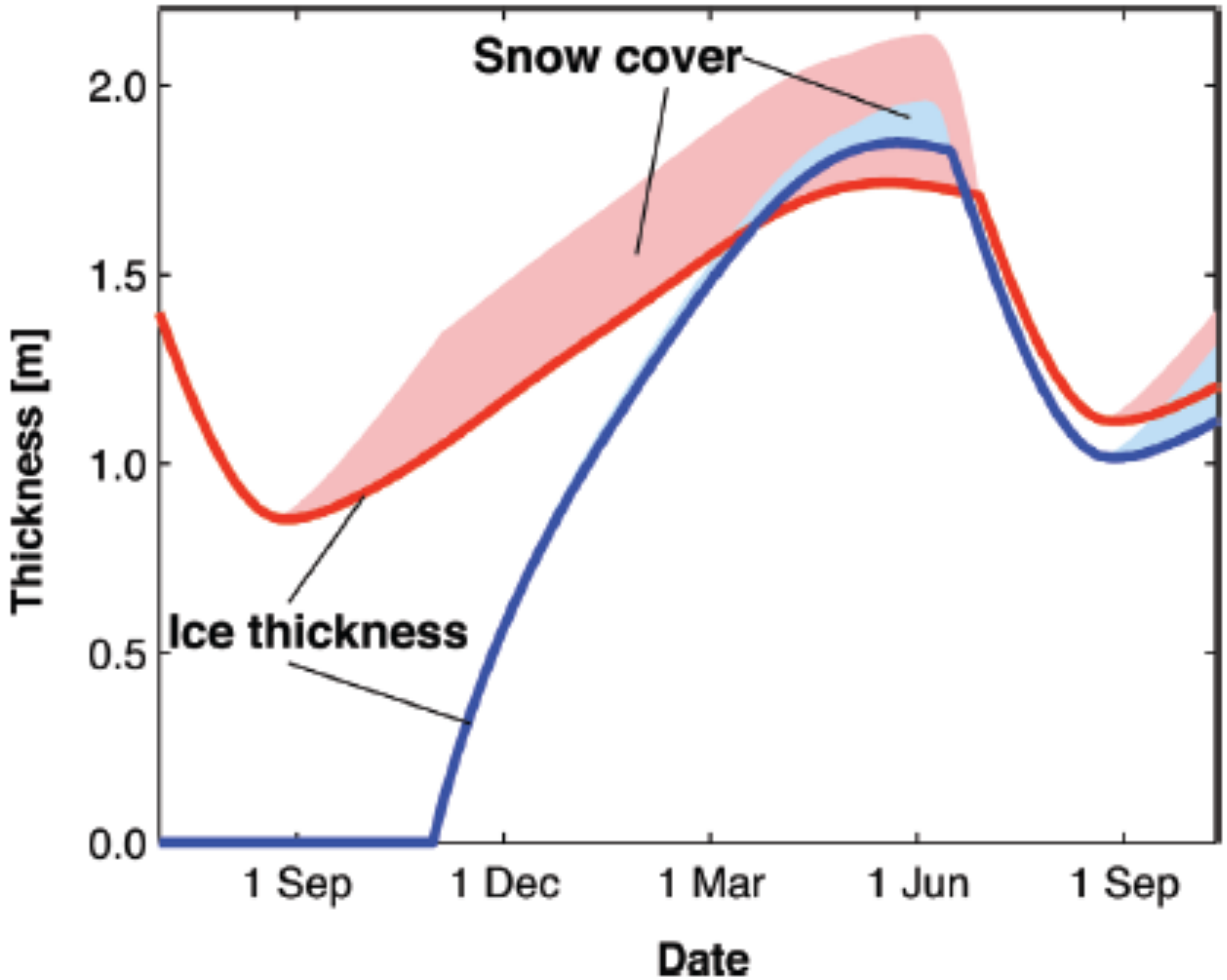


Figure from:

The future of ice sheets and sea ice: Between reversible retreat and unstoppable loss

Dirk Notz[1]

PNAS | December 8, 2009 | vol. 106 | no. 49 | 20595

The 0-d model

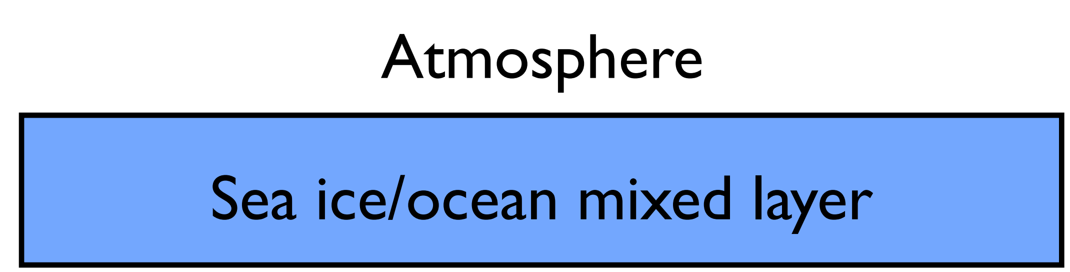
("EW09": Eisenman & Wettlaufer, PNAS 2009)

State variable *E(t)*: average energy per unit surface area (relative to Arctic ocean mixed layer at the freezing point)

$$E(t) = \begin{cases} -L_i h_i(t) & \text{if } E < 0 \quad (i.e.\ E \propto \text{ice thickness } h_i) \\ C_s T(t) & \text{if } E \geq 0 \quad (i.e.\ E \propto \text{mixed layer temp. } T) \end{cases}$$

$L_i =$ **latent heat of fusion of ice**

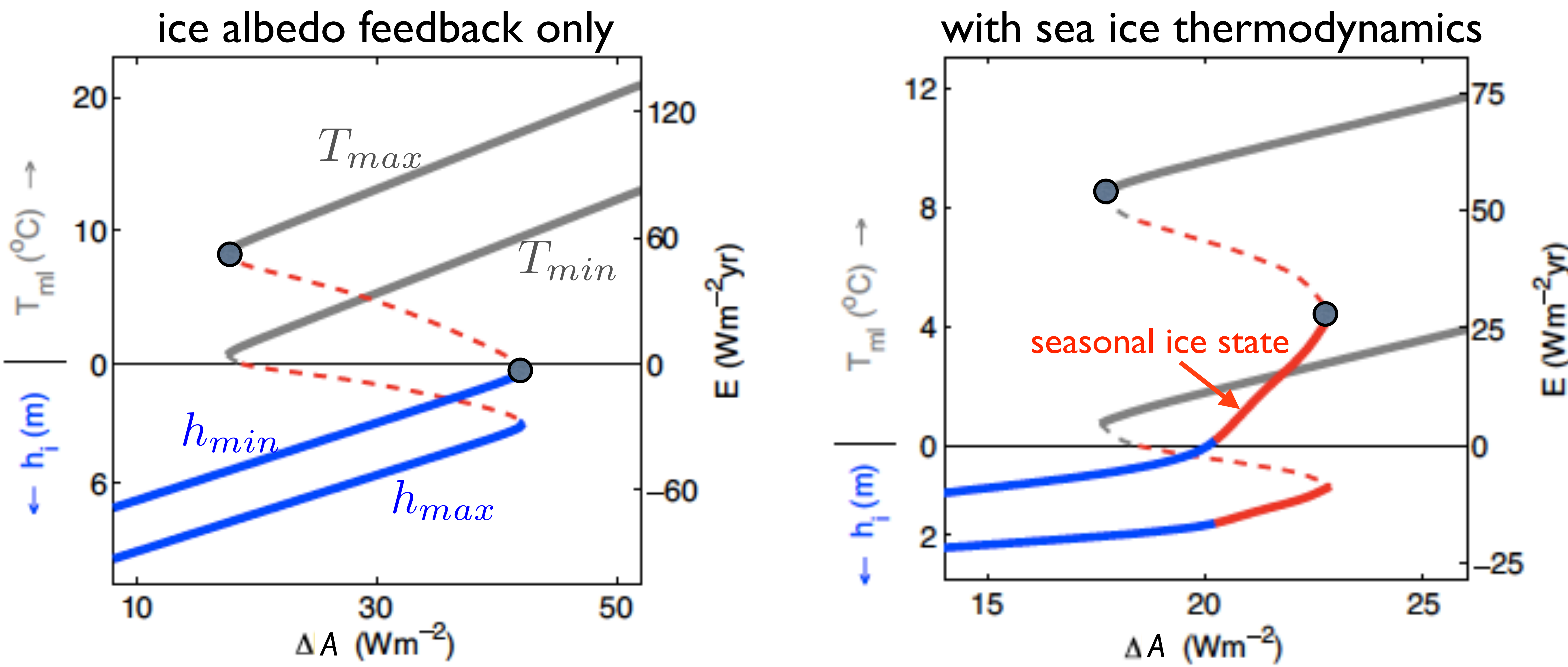
$C_s =$ **ocean heat capacity per unit surface area**



EW09 results:

(Eisenman & Wettlaufer, PNAS 2009)

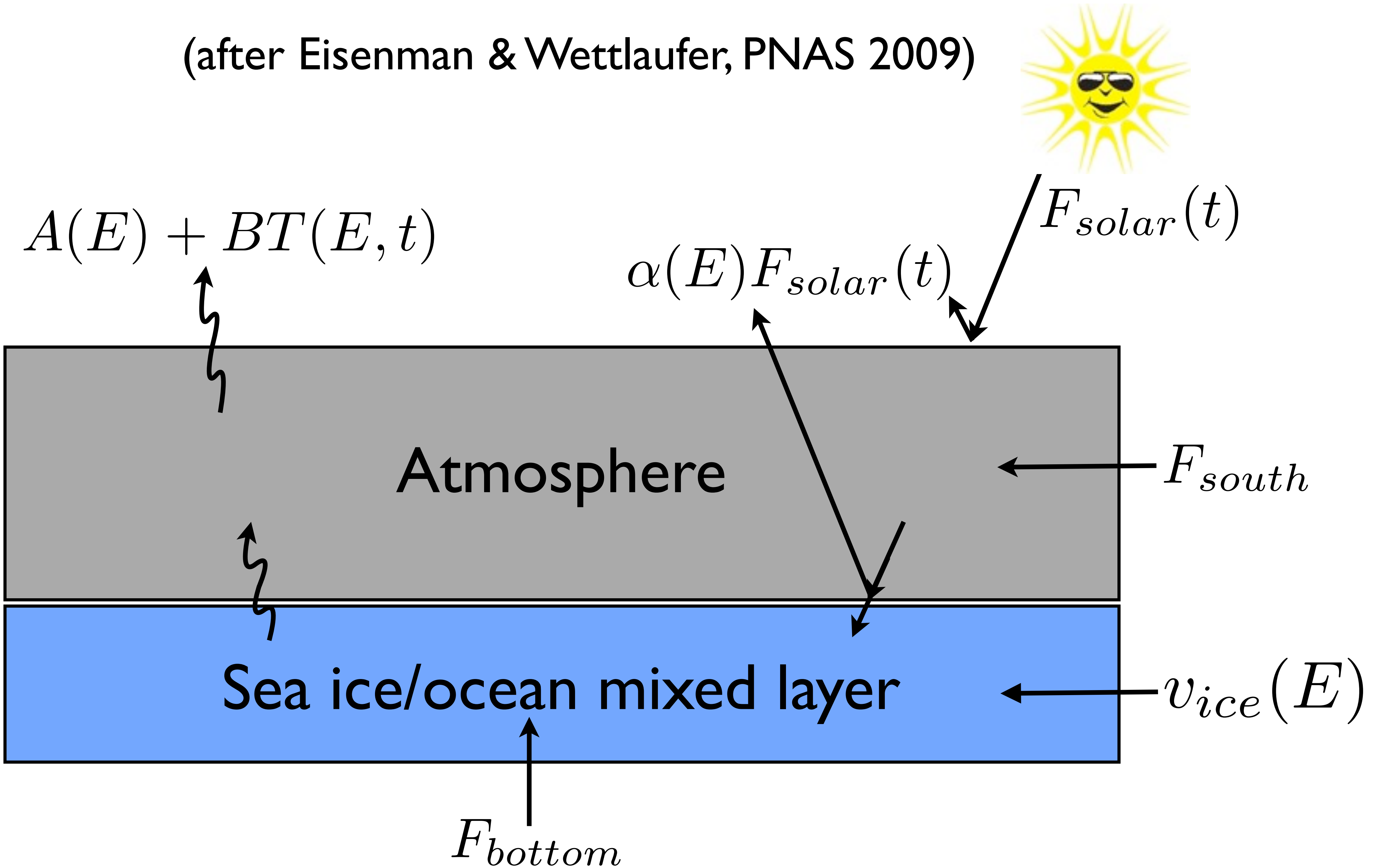
the role of sea ice thermodynamics: no summer tipping point?



greenhouse gases ⟶

The 0-d model

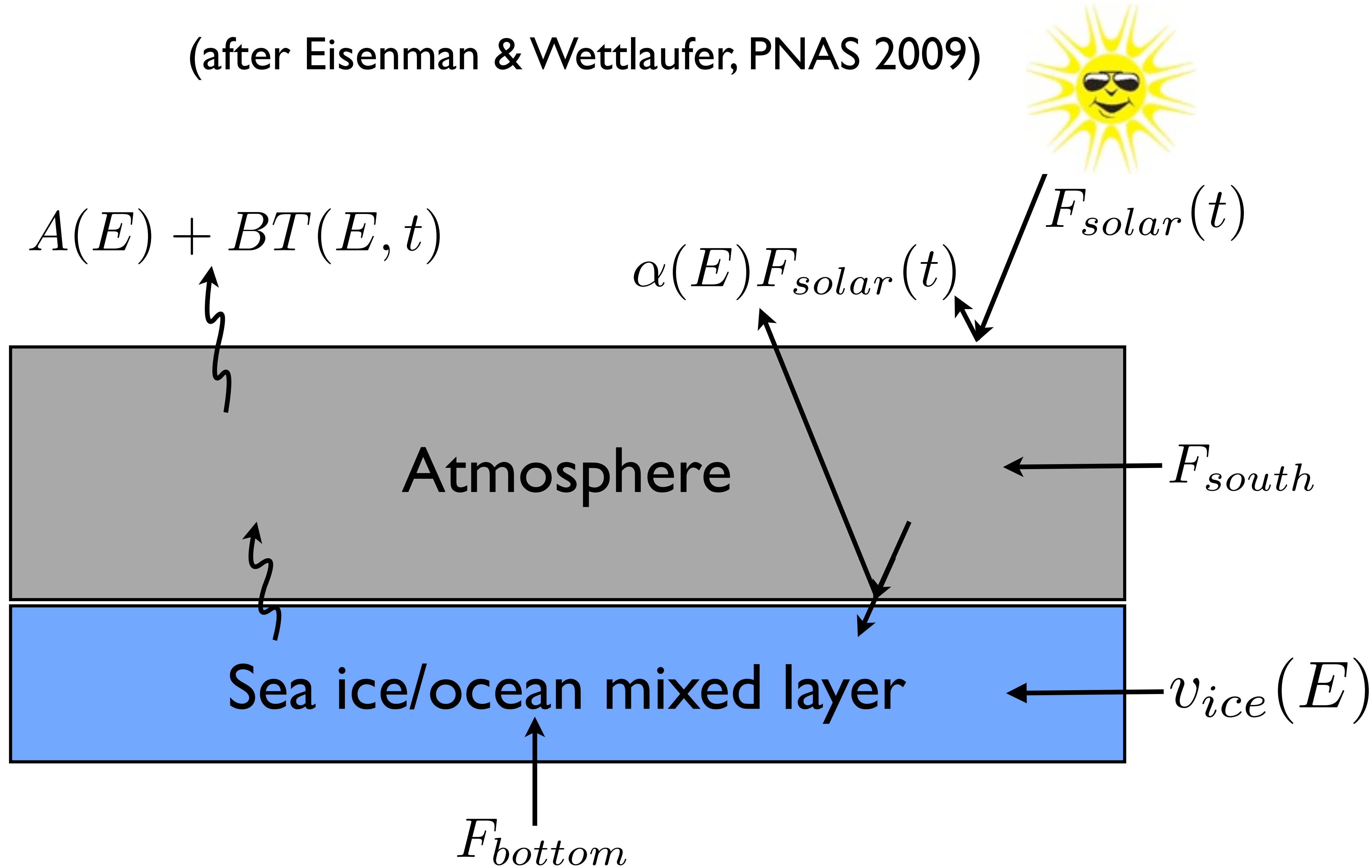
(after Eisenman & Wettlaufer, PNAS 2009)



$$\frac{dE}{dt} = [1 - \alpha(E)]F_{solar}(t) + F_{bottom} + F_{south} + v_{ice}(E) - [A(E) + BT(E,t)]$$

The 0-d model

(after Eisenman & Wettlaufer, PNAS 2009)



$$\frac{dE}{dt} = [1-\alpha(E)]F_{solar}(t) + F_{bottom} + F_{south} + v_{ice}(E) - [A(E) + BT(E,t)]$$

constants

~E (for E<0, otherwise 0)

“Top of the Atmosphere albedo”

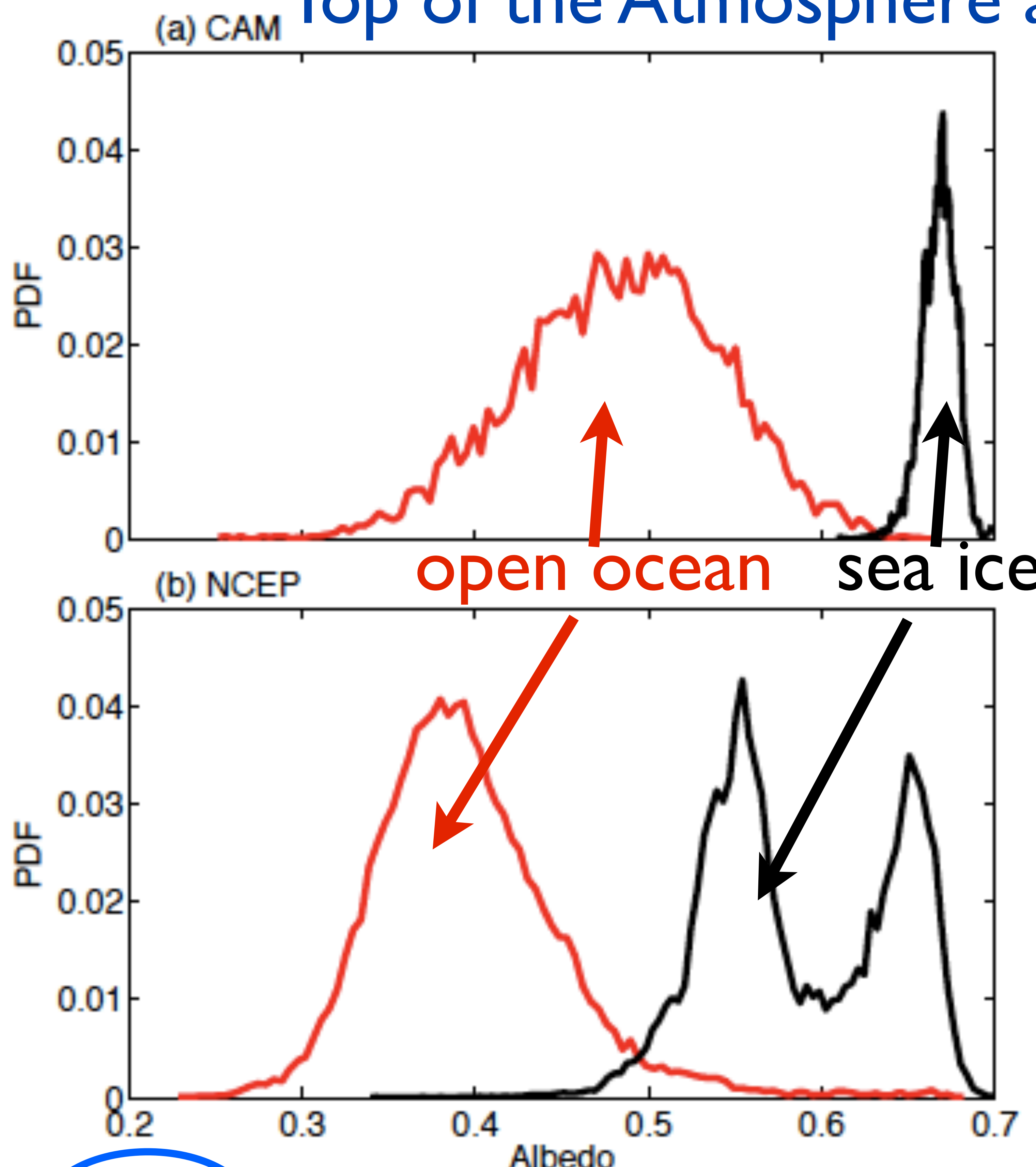


Figure from Abbot, Silber, Pierrehumbert 2011

(CAM=GCM)

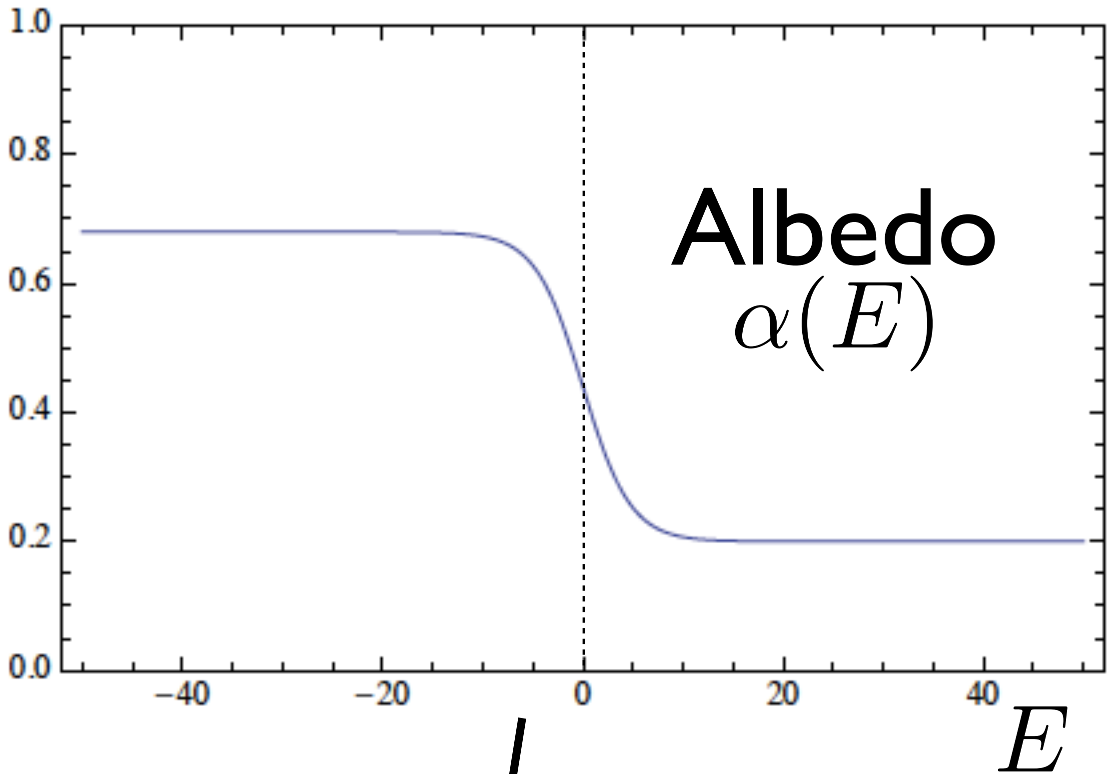
(NCEP=Observation)

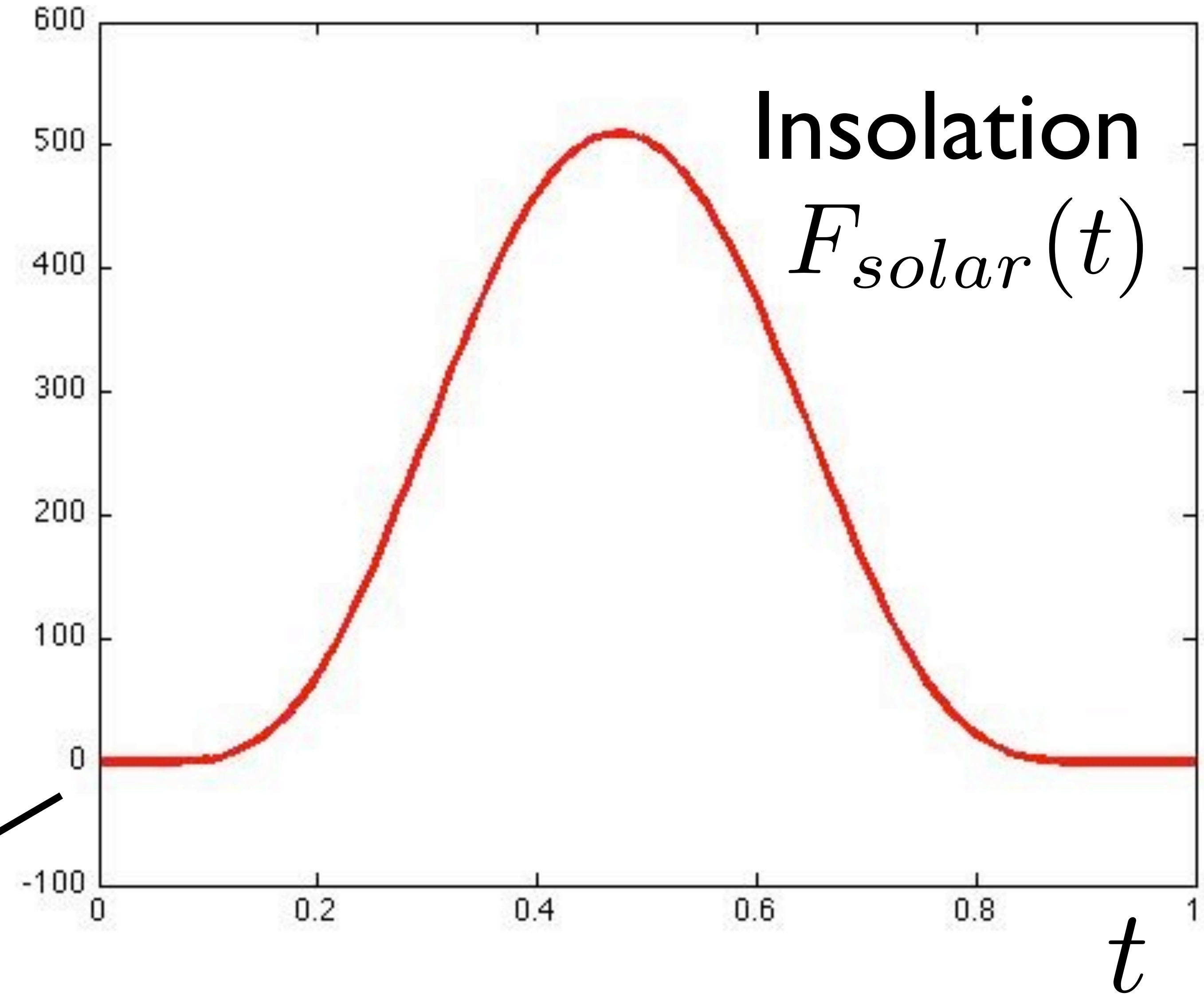
$$\frac{dE}{dt} = [1 - \alpha(E)]F_{solar}(t) + F_{bottom} + F_{south} + v_{ice}(E) - [A(E) + BT(E,t)]$$

The 0-d model

(after Eisenman & Wettlaufer, PNAS 2009)

Incoming Solar Radiation: Positive Ice Albedo feedback





$$\frac{dE}{dt} = [1 - \alpha(E)]F_{solar}(t) + F_{bottom} + F_{south} + v_{ice}(E) - [A(E) + BT(E,t)]$$

“Outgoing long wave radiation”

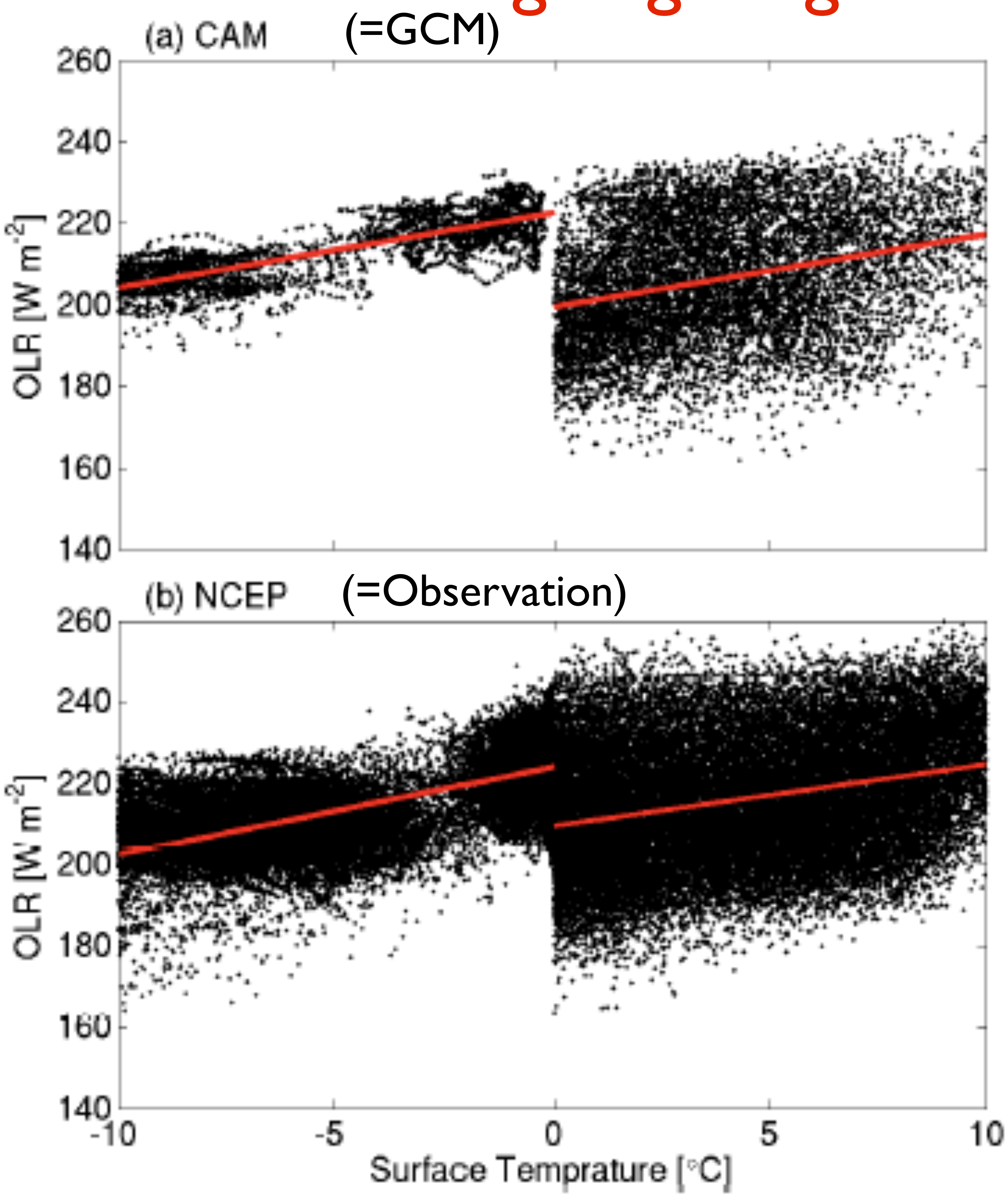
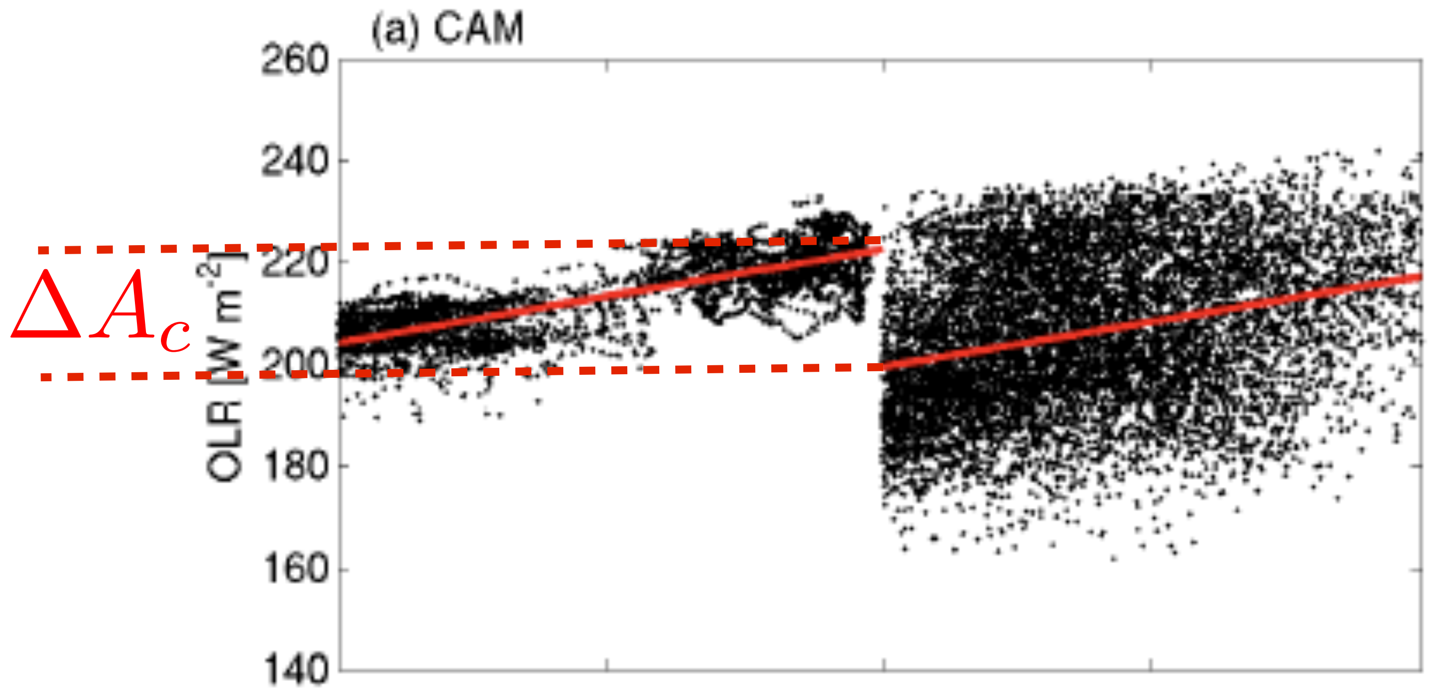
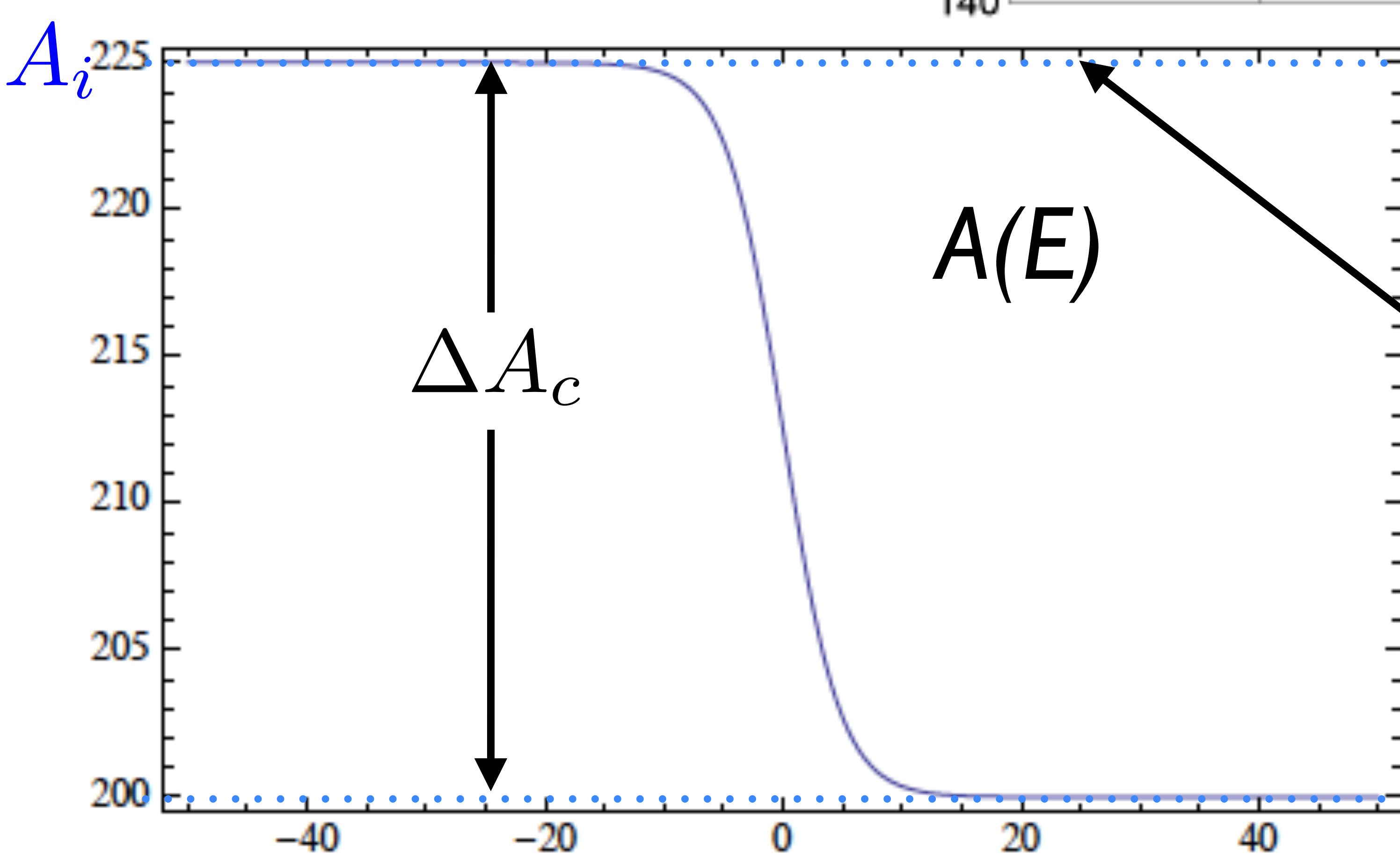


Figure from Abbot, Silber, Pierrehumbert 2011

$$\frac{dE}{dt} = [1 - \alpha(E)]F_{solar}(t) + F_{bottom} + F_{south} + v_{ice}(E) - [A(E) + BT(E,t)]$$

"Outgoing long wave radiation"





"Long-wave cloud feedback"

$$A_i = A_0 - \Delta A_{ghg}$$

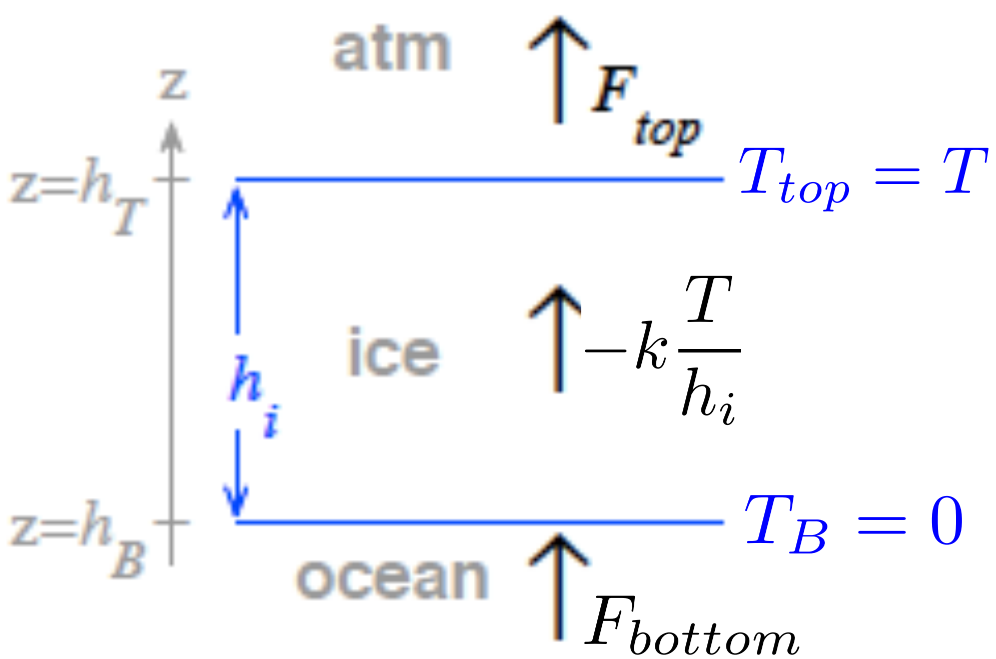
$$\frac{dE}{dt} = [1 - \alpha(E)]F_{solar}(t) + F_{bottom} + F_{south} + v_{ice}(E) - [A(E) + BT(E,t)]$$

The 0-d model

(after Eisenman & Wettlaufer, PNAS 2009)

$$E(t) = \begin{cases} -L_i h_i(t) & \text{if } E < 0 \quad (i.e.\ E \propto \text{ice thickness } h_i) \\ C_s T(t) & \text{if } E \geq 0 \quad (i.e.\ E \propto \text{mixed layer temp. } T) \end{cases}$$

Sea-ice thermodynamics (*E<0*)



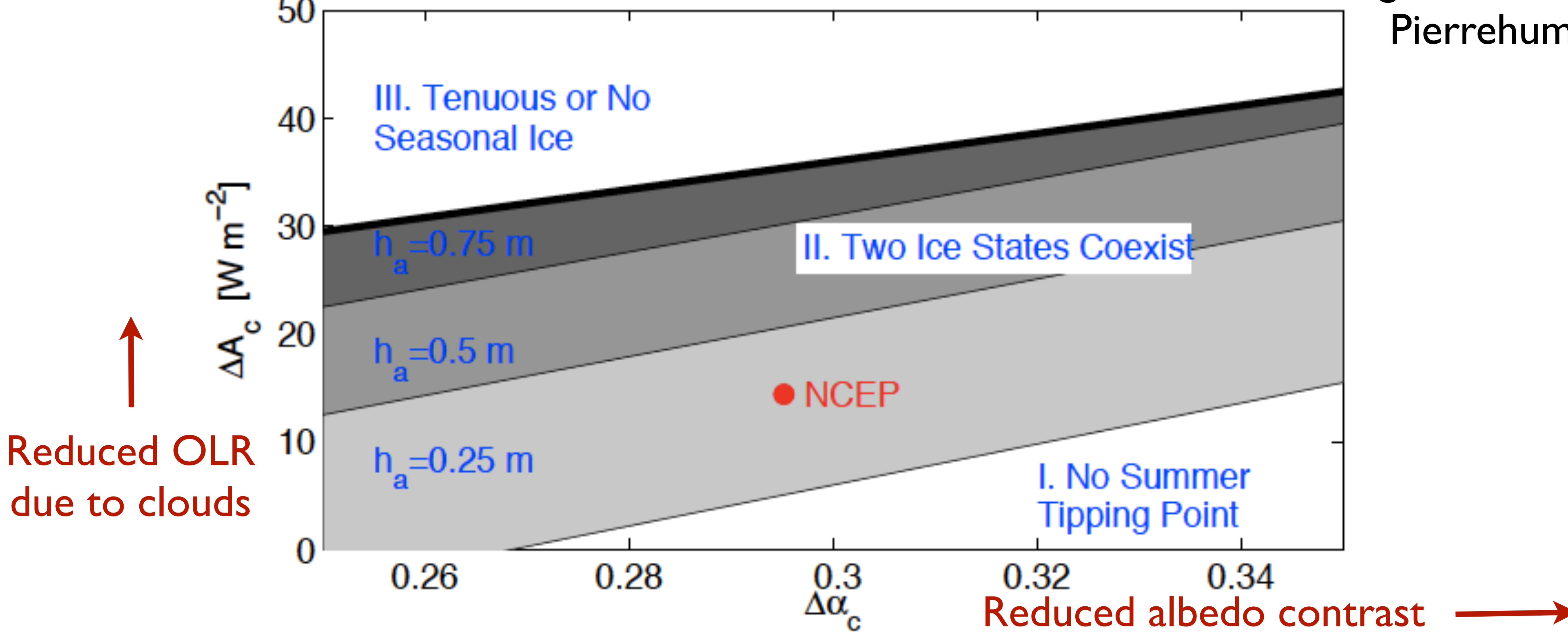
$$F_{top} = \begin{cases} -k\frac{T}{h_i} & \text{if } T < 0 \ (F_{top} > 0) \\ L_i \frac{dh_T}{dt} & \text{if } T = 0 \ (F_{top} \leq 0) \end{cases}$$

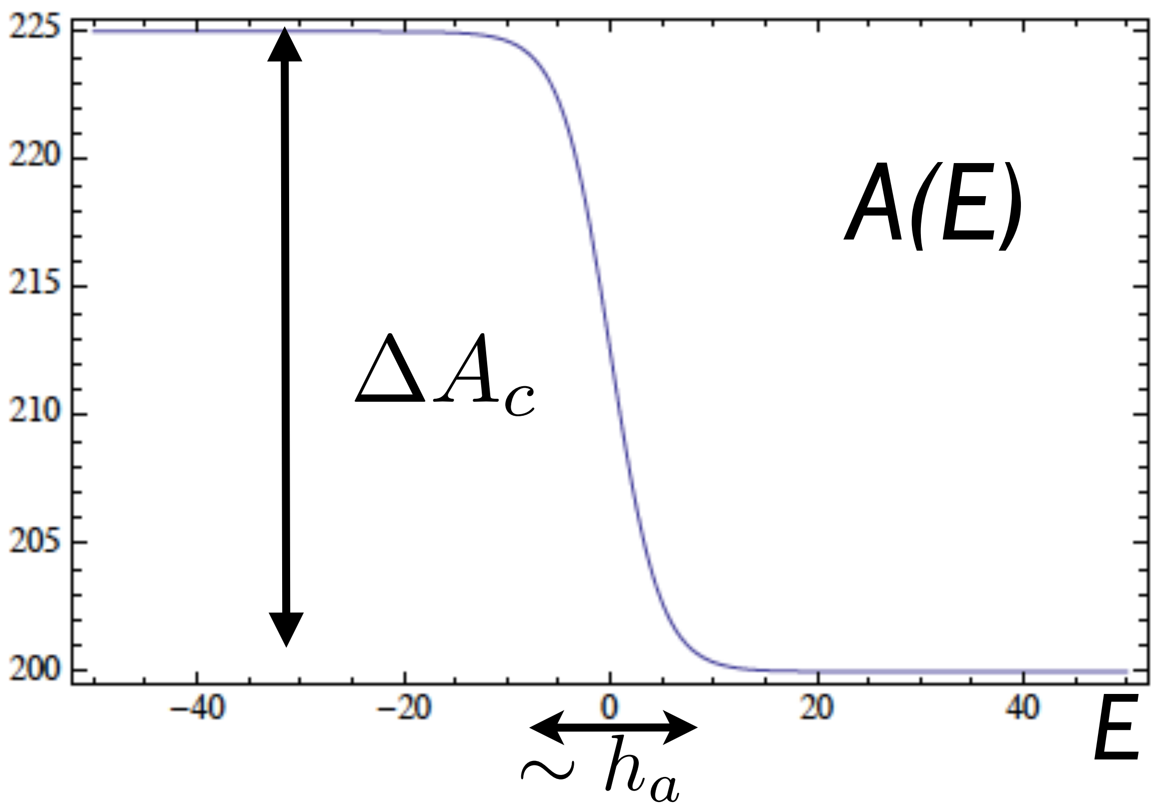
$$\begin{aligned} F_{top} &= F^{out}_{surface} - F^{in}_{surface} \\ &= [A + BT - F_{south}] - [1-\alpha]F_{solar} \end{aligned}$$

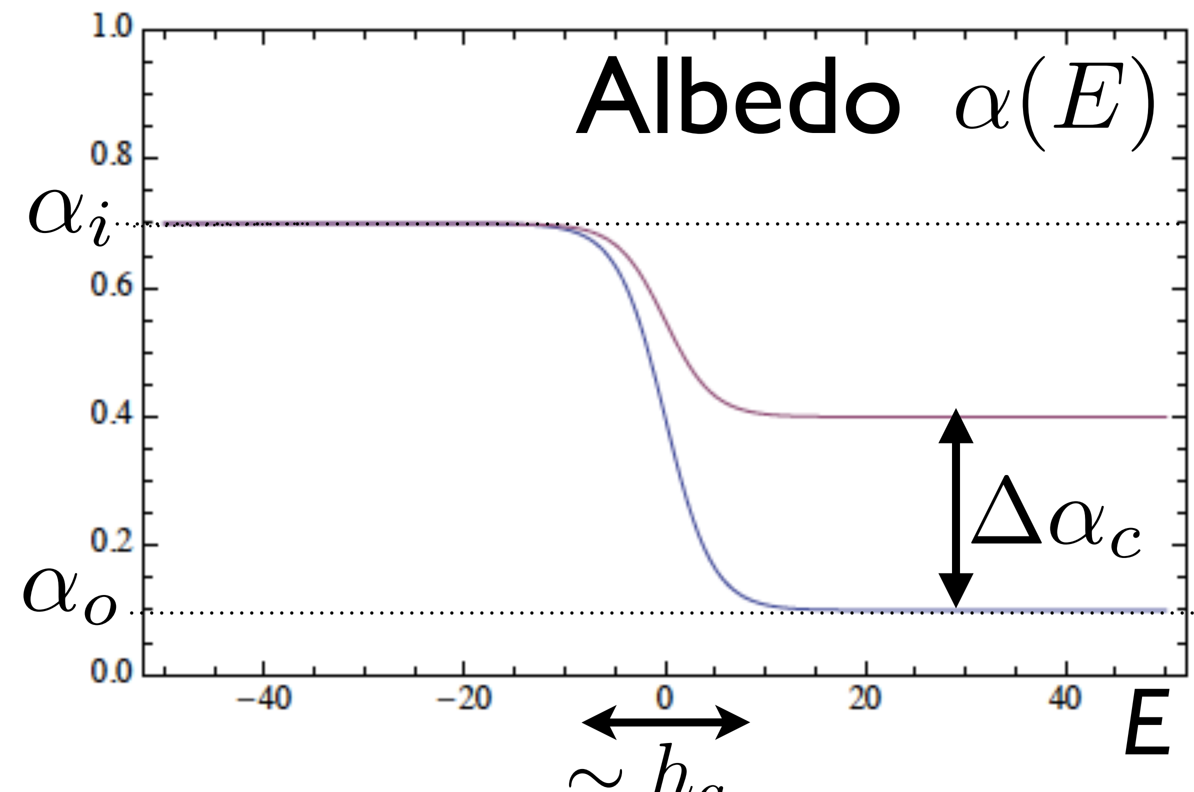
$$\frac{dE}{dt} = [1-\alpha(E)]F_{solar}(t) + F_{bottom} + F_{south} + v_{ice}(E) - [A(E) + BT(E,t)]$$

“cloud feedbacks”: no summer tipping point?

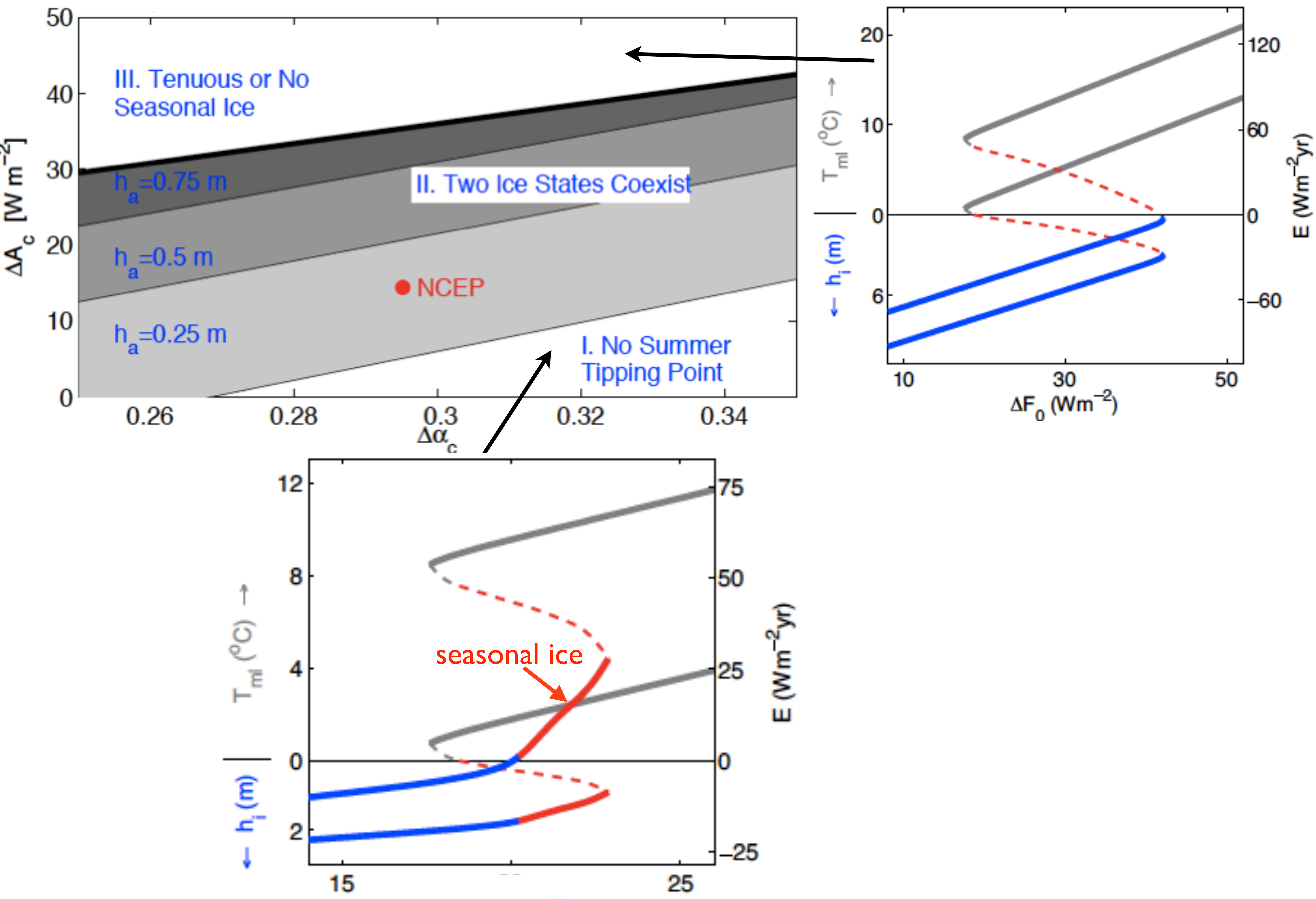
Figure from Abbot, Silber, Pierrehumbert 2011



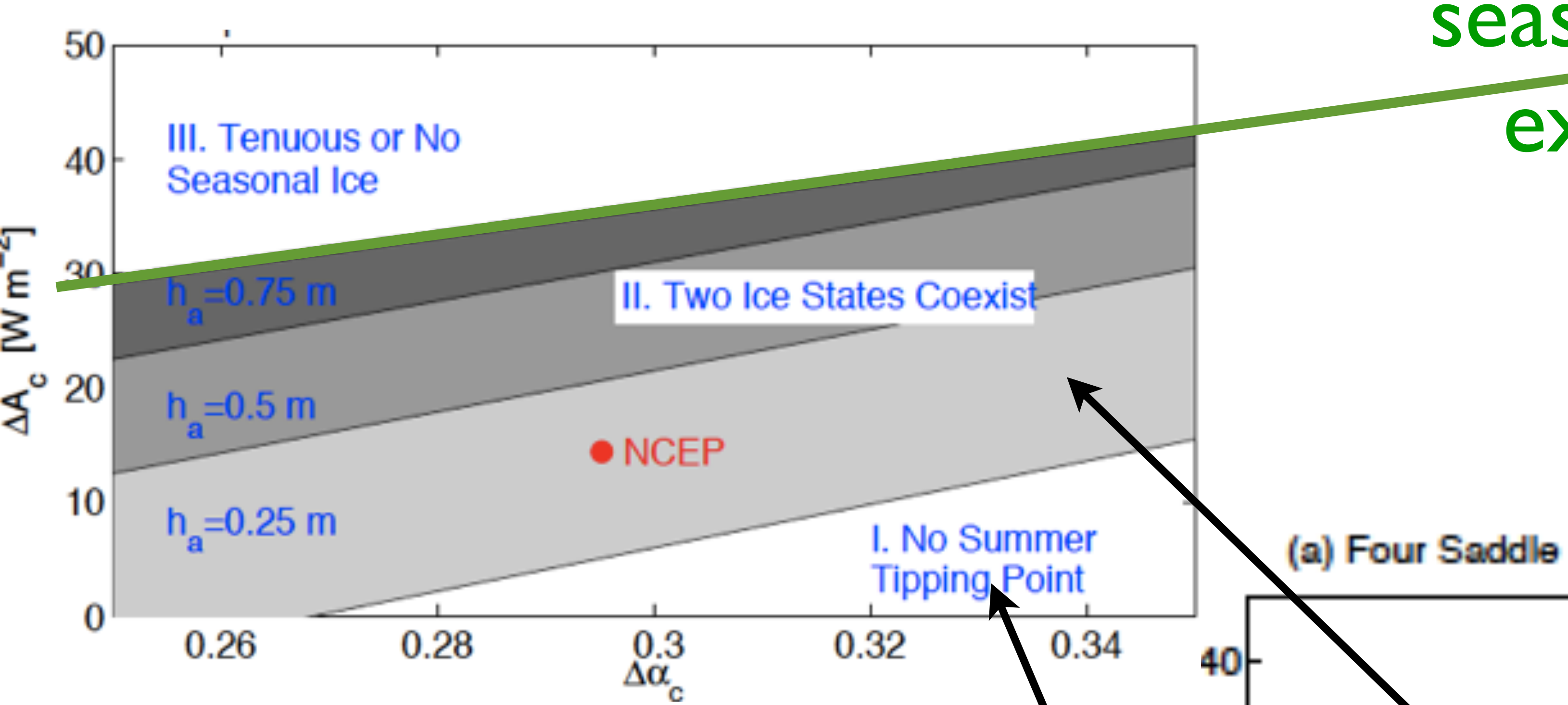


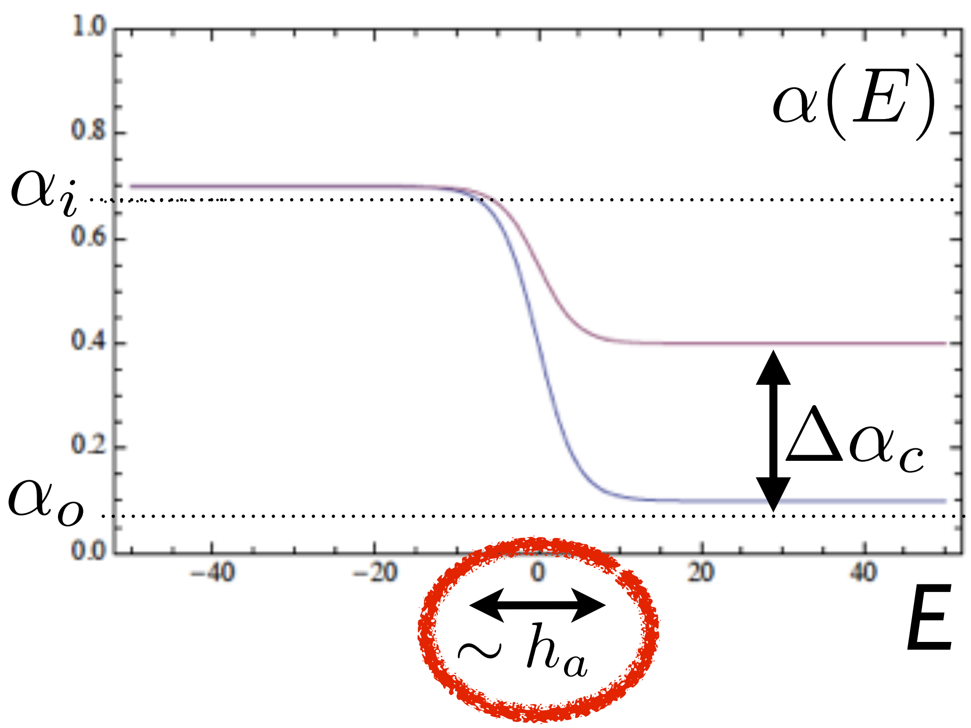


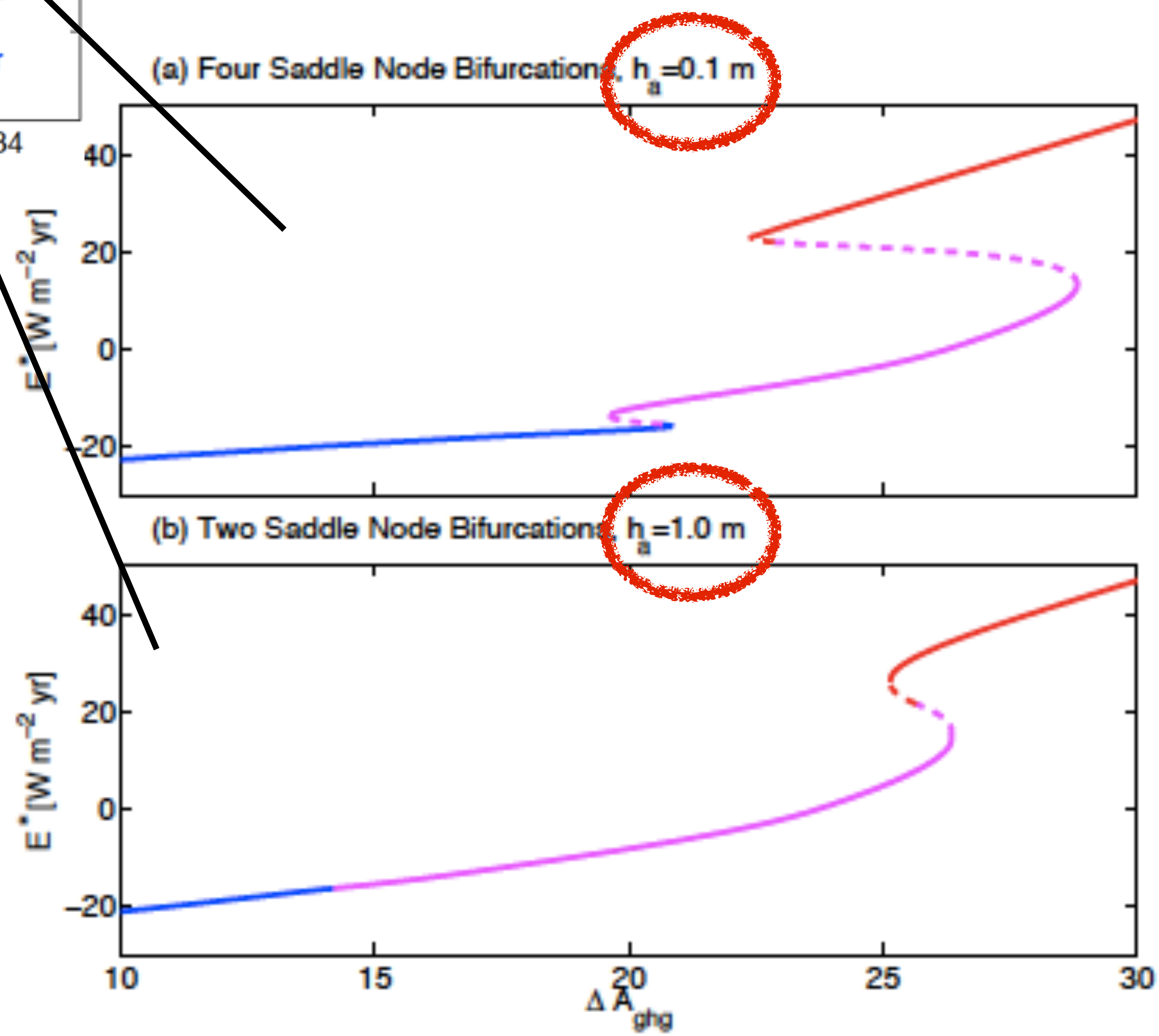
cf. EW09 results



seasonal ice-free states: existence boundary



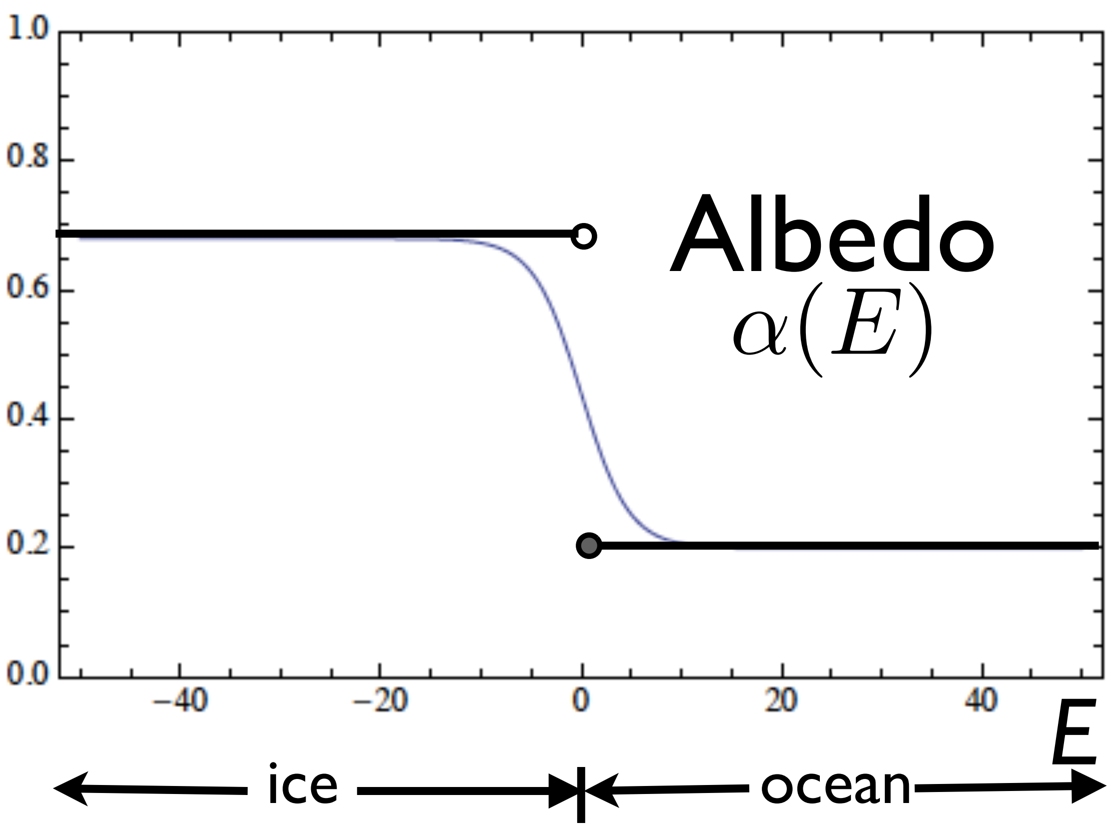


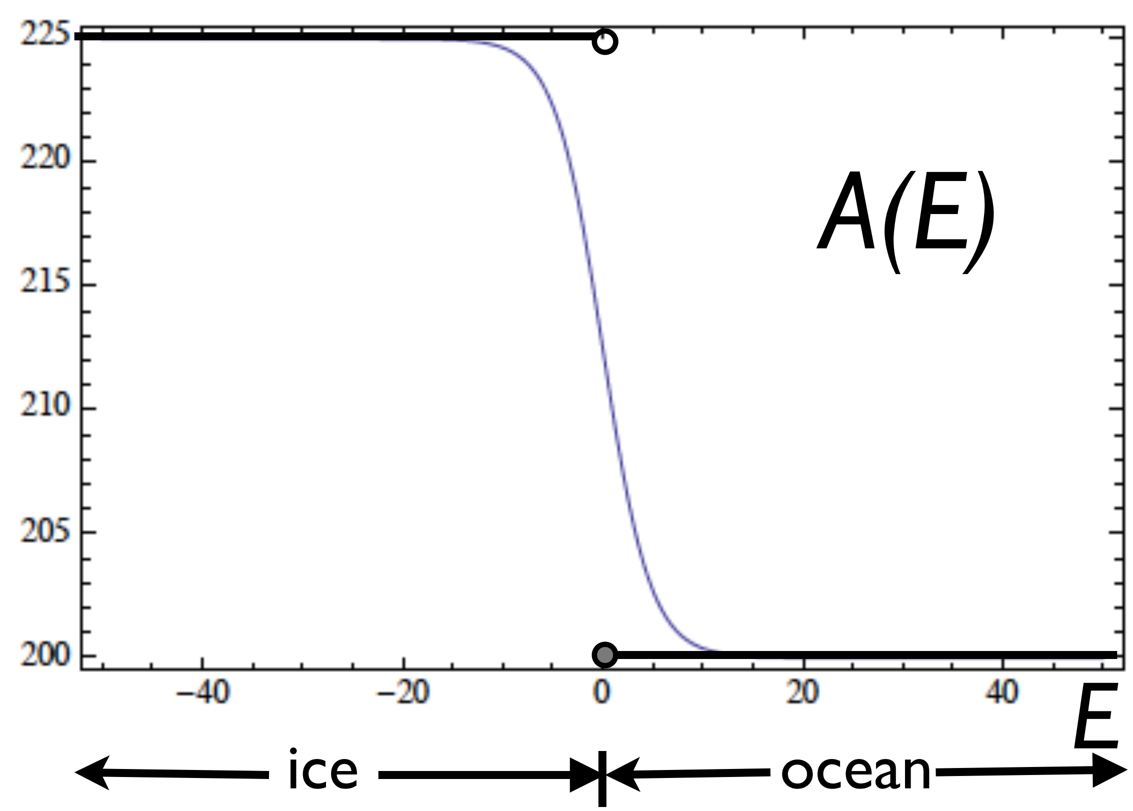


Some analysis:

determining existence conditions for seasonally ice-free states

Approximation: piecewise constant α(*E*) and *A(E)*

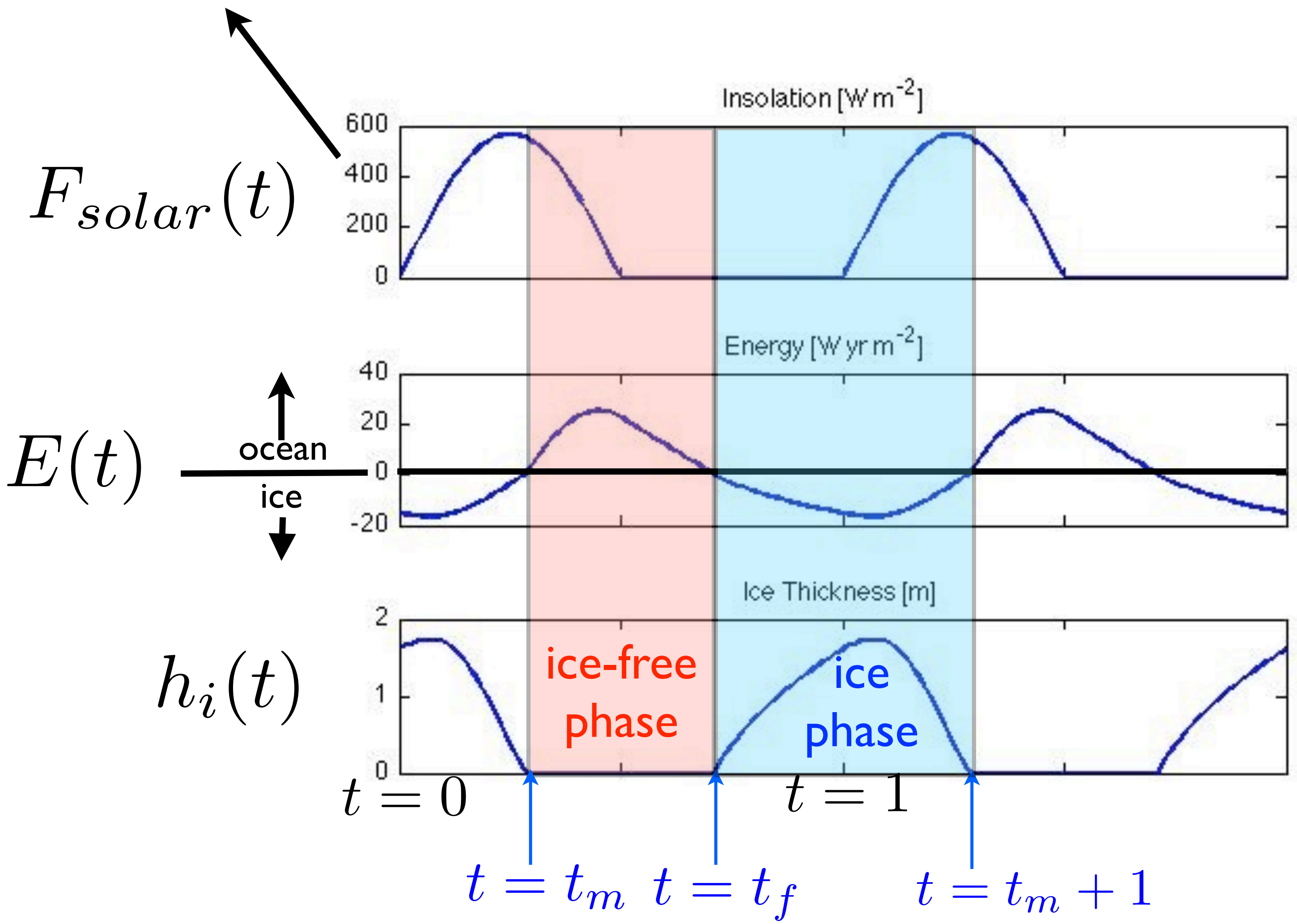




$$\frac{dE}{dt} = [1 - \alpha(E)]F_{solar}(t) + F_{bottom} + F_{south} + v_{ice}(E) - [A(E) + BT(E,t)]$$

Existence conditions for seasonally ice-free states

$$\frac{dE}{dt} = [1-\alpha(E)]F_{solar}(t) + F_{bottom} + F_{south} + v_{ice}(E) - [A(E) + BT(E,t)]$$



Periodic solutions: fixed points of appropriate Poincaré map $(P = P_i \circ P_o)$

$$(t=t_m, E=0) \underset{E\geq 0}{\overset{P_o}{\rightarrow}} (t=t_f, E=0) \underset{E<0}{\overset{P_i}{\rightarrow}} (t=t_m+1, E=0)\ldots ad\ infinitum$$

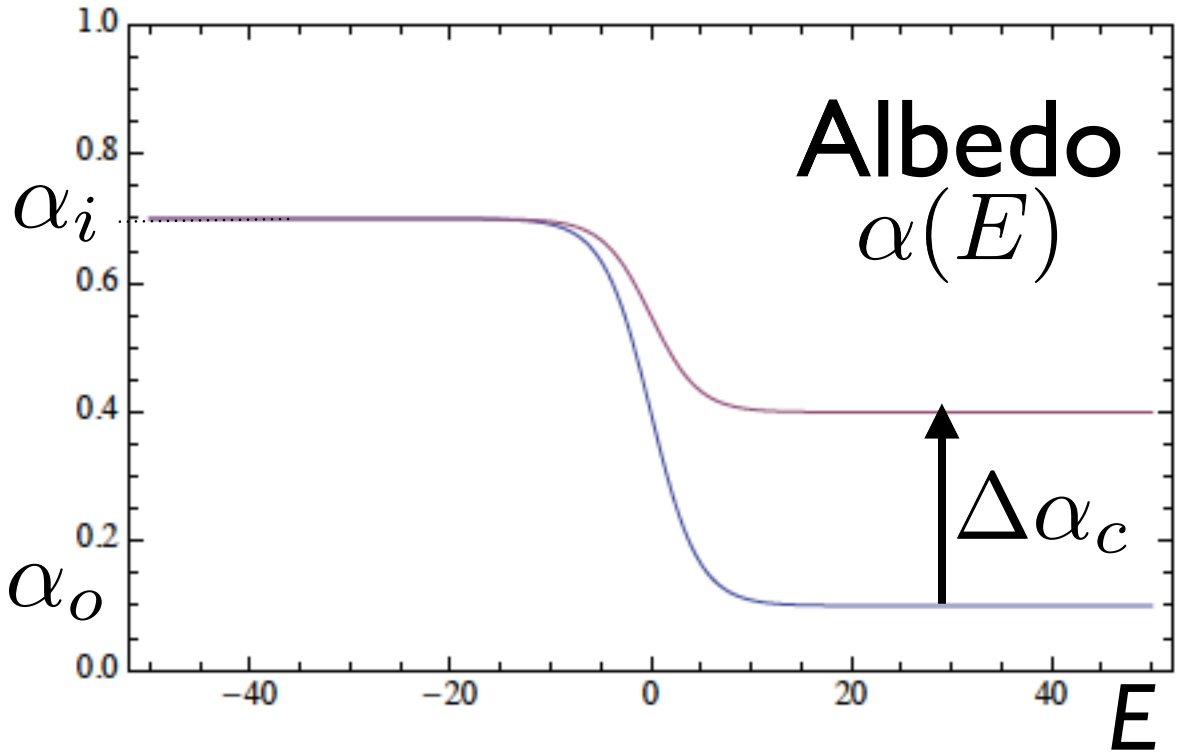
Existence conditions for seasonally ice-free states

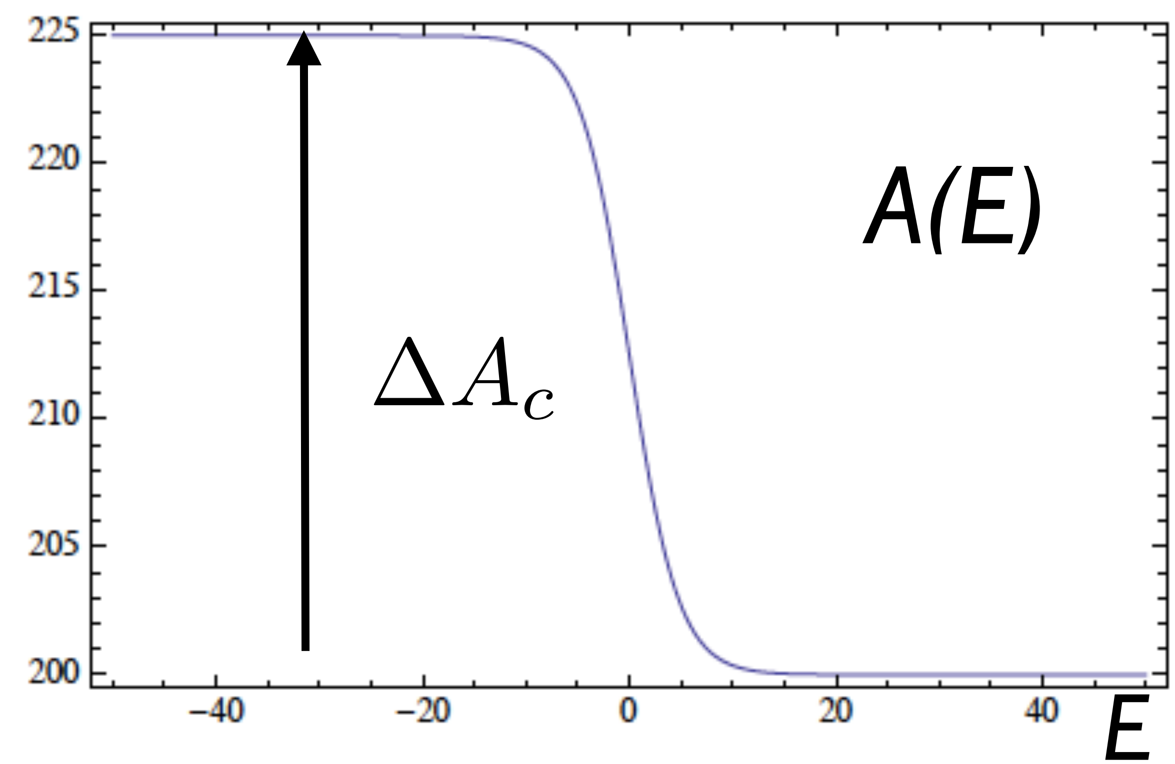
Periodic solutions: fixed points of appropriate Poincaré map $(P = P_i \circ P_o)$

$$(t = t_m, E = 0) \underset{E \geq 0}{\overset{P_o}{\rightarrow}} (t = t_f, E = 0) \underset{E < 0}{\overset{P_i}{\rightarrow}} (t = t_m + 1, E = 0) \ldots ad\ infinitum$$

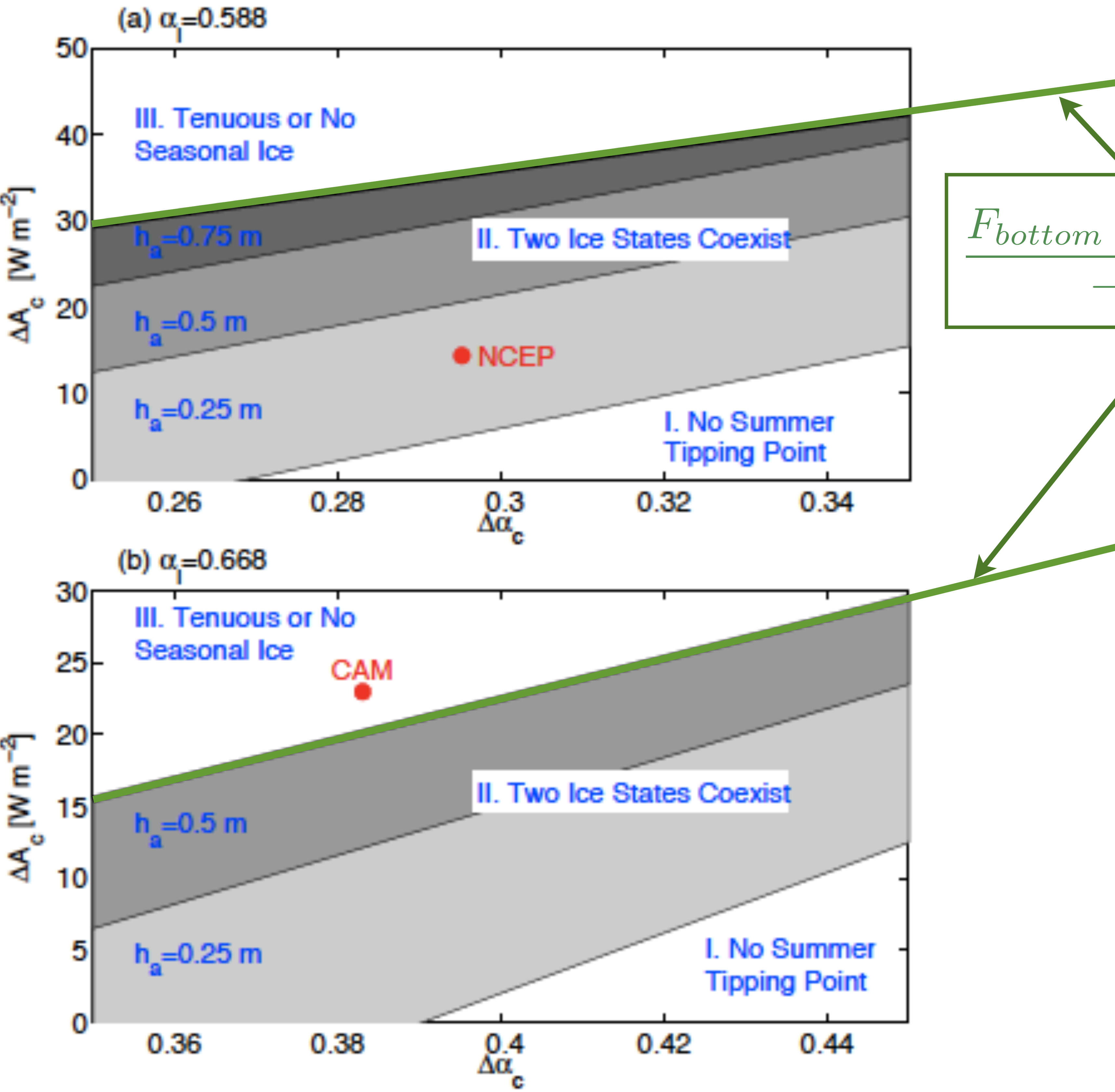
$$P_o(E = 0; t_m, t_f, A - \underline{\Delta A_c}, \alpha_o + \underline{\Delta \alpha_c}) = 0$$

$$P_i(E = 0; t_m, t_f, A, \alpha_i) = 0$$



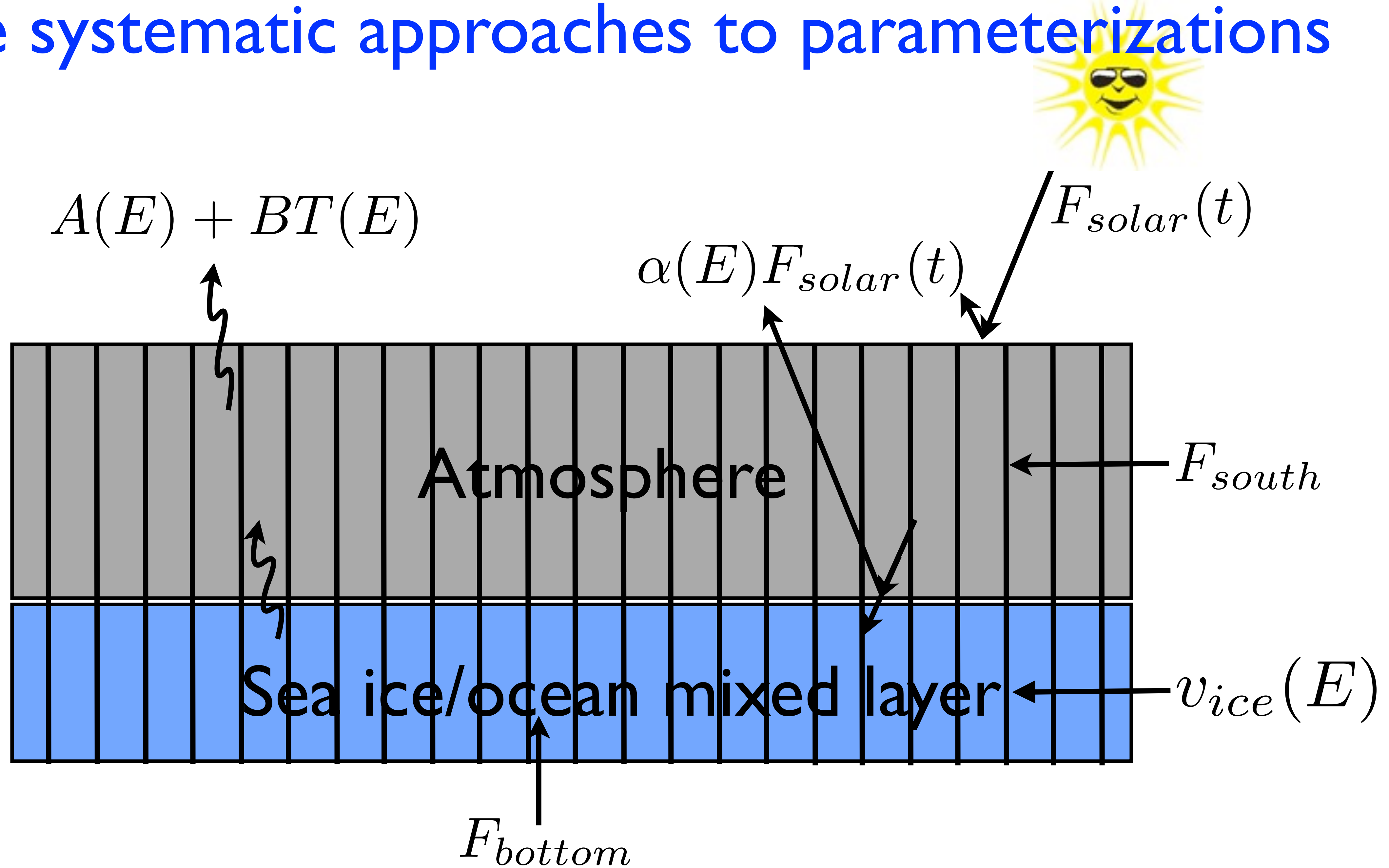


$$\frac{dE}{dt} + \frac{BE}{C_s} = [1 - \alpha_o - \Delta\alpha_c]F_{solar}(t) + [F_{bottom} + F_{south} - A + \Delta A_c]$$



$$\frac{F_{bottom} + F_{south} - A + \Delta A_c}{-1 + \alpha_o + \Delta\alpha_c} = Constant$$

Future direction:
More systematic approaches to parameterizations



e.g. if *E*=average surface energy density in the Arctic region, then

$$\frac{dE}{dt} \overset{?}{=} [1 - \alpha(E)]F_{solar}(t) + F_{bottom} + F_{south} + v_{ice}(E) - [A(E) + BT(E,t)]$$

?

Summary Slide (1 of 6 closing slides)

We performed a bifurcation analysis on a variation of the Eisenman and Wettlaufer 2009 energy balance model of Arctic sea ice loss.

Three distinct parameter regimes were found, which vary in the number and types of tipping points.

Results are sensitive to how the albedo is smoothed over the transition from an ice-covered to an ice-free Arctic.

This points to some of the challenges inherent in mathematical modeling of climate....

Questions I didn’t answer:

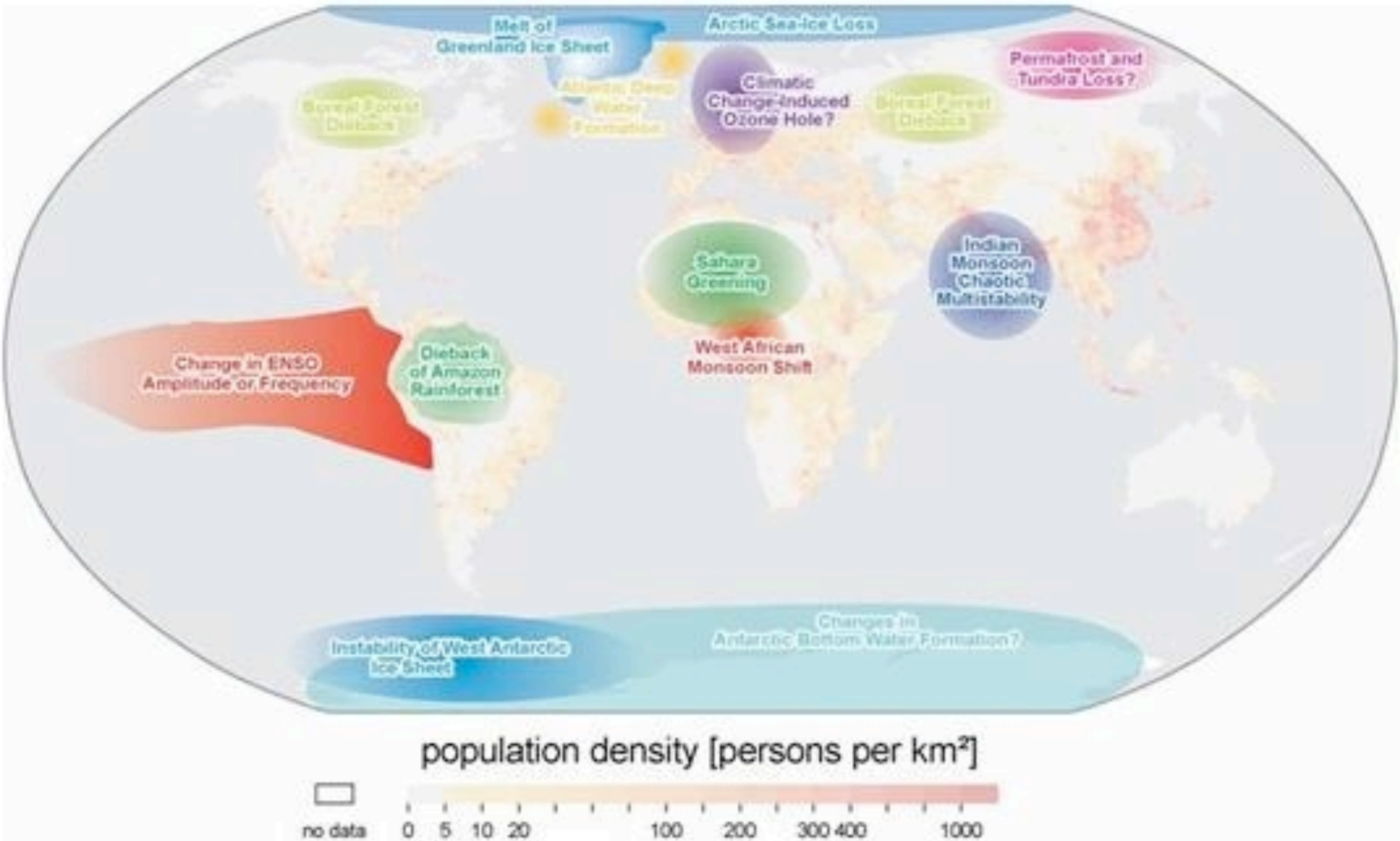
What is a tipping point? And are we close to one for Arctic sea ice loss? If so, how bad will it be?

Could we tell in advance of crossing one? And, if so, what should we be measuring to know its proximity?

Arctic sea ice loss:
the tip of the iceberg for climate tipping points

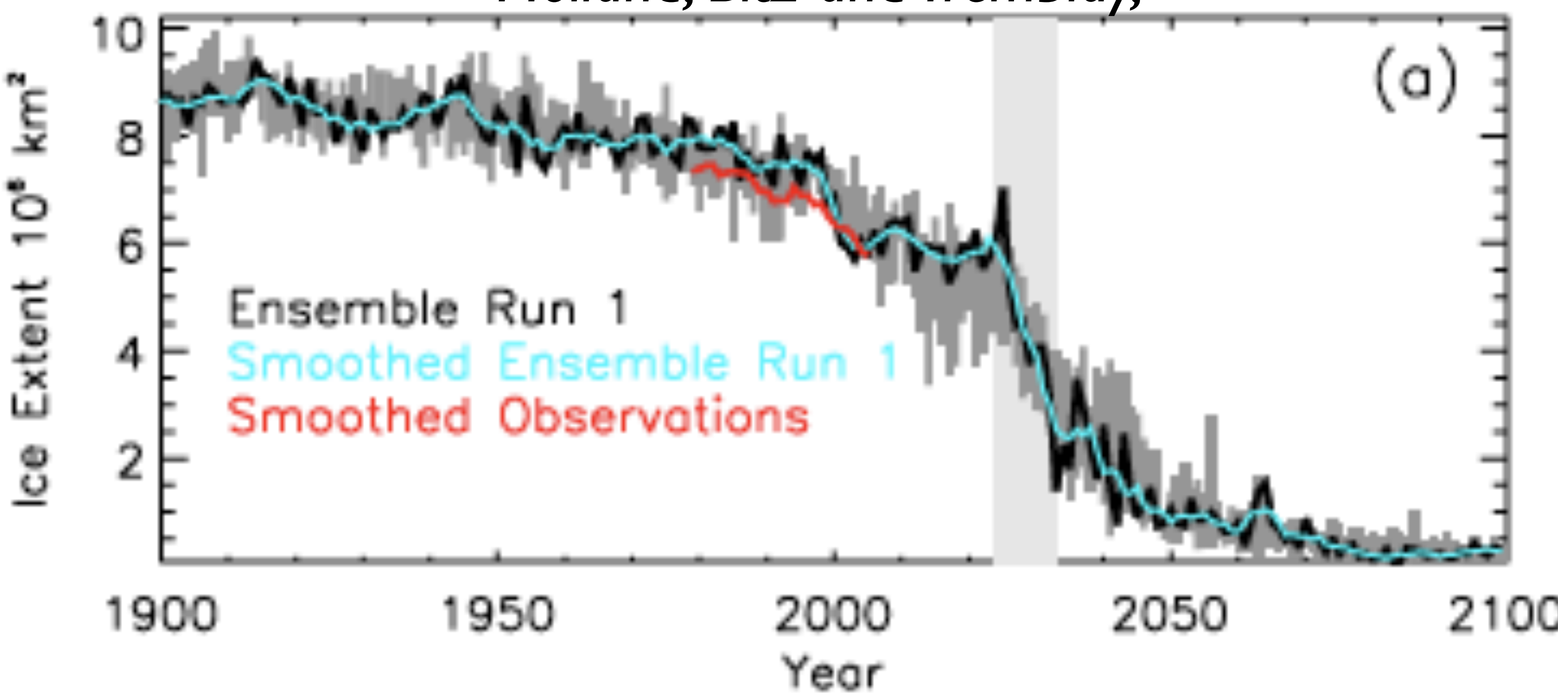
TIPPING POINTS IN THE EARTH SYSTEM
Lenton et al., 2008, PNAS

"Policy-Relevant Tipping Elements"?



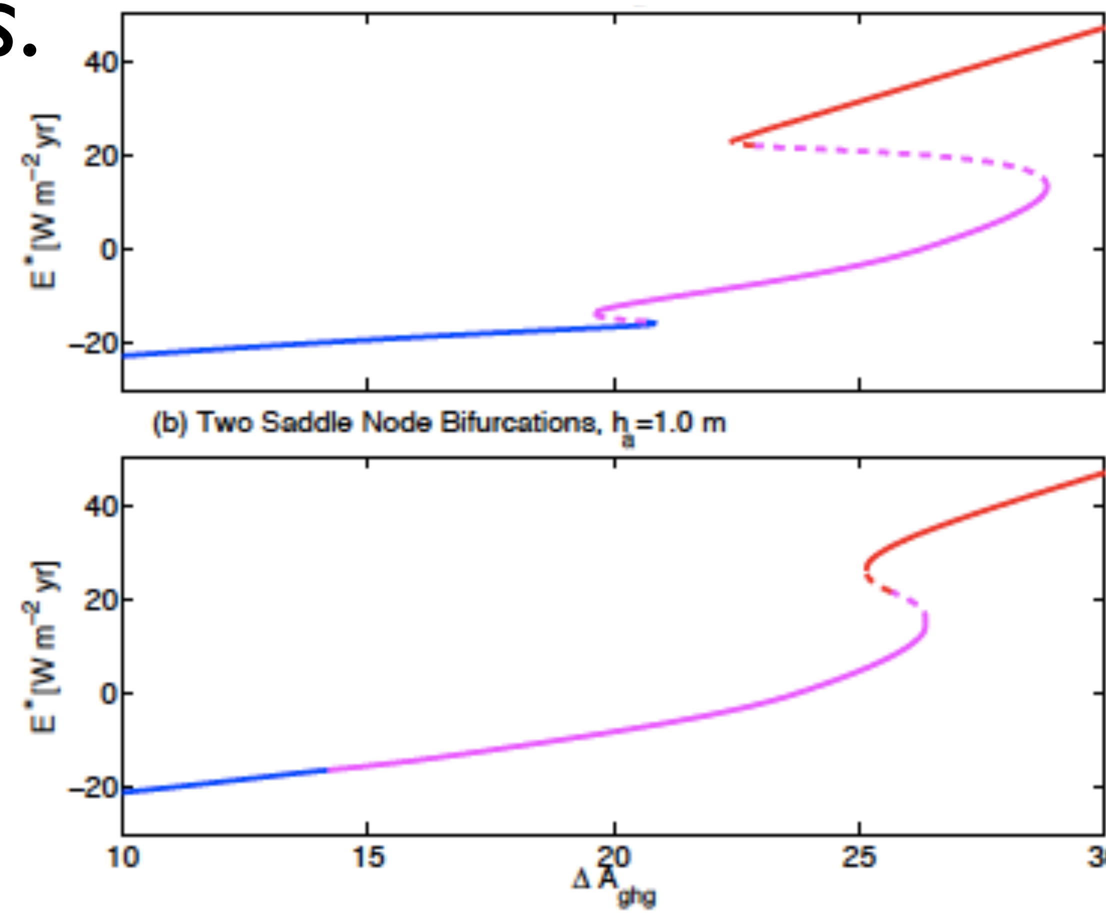
Future directions:
What is a good signature of a bifurcation in a GCM?

Holland, Bitz and Tremblay,



vs.

Abbot, Silber & Pierrehumbert,



see, for example,

Held and Kleinen, GRL 2004

Livina and Lenton, GRL 2007

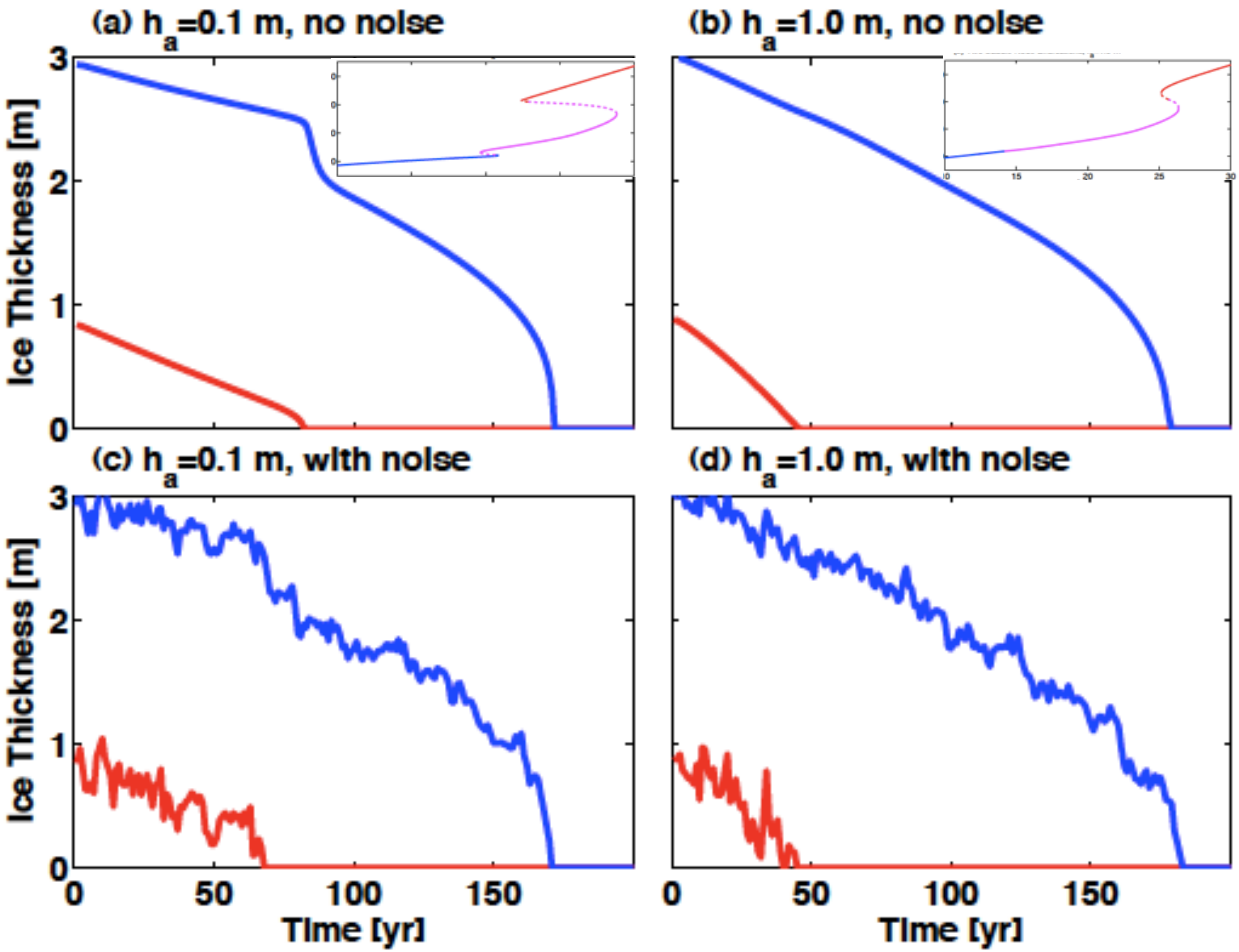
Dakos, et al. PNAS 2008

Thompson & Sieber 2010/2011 papers

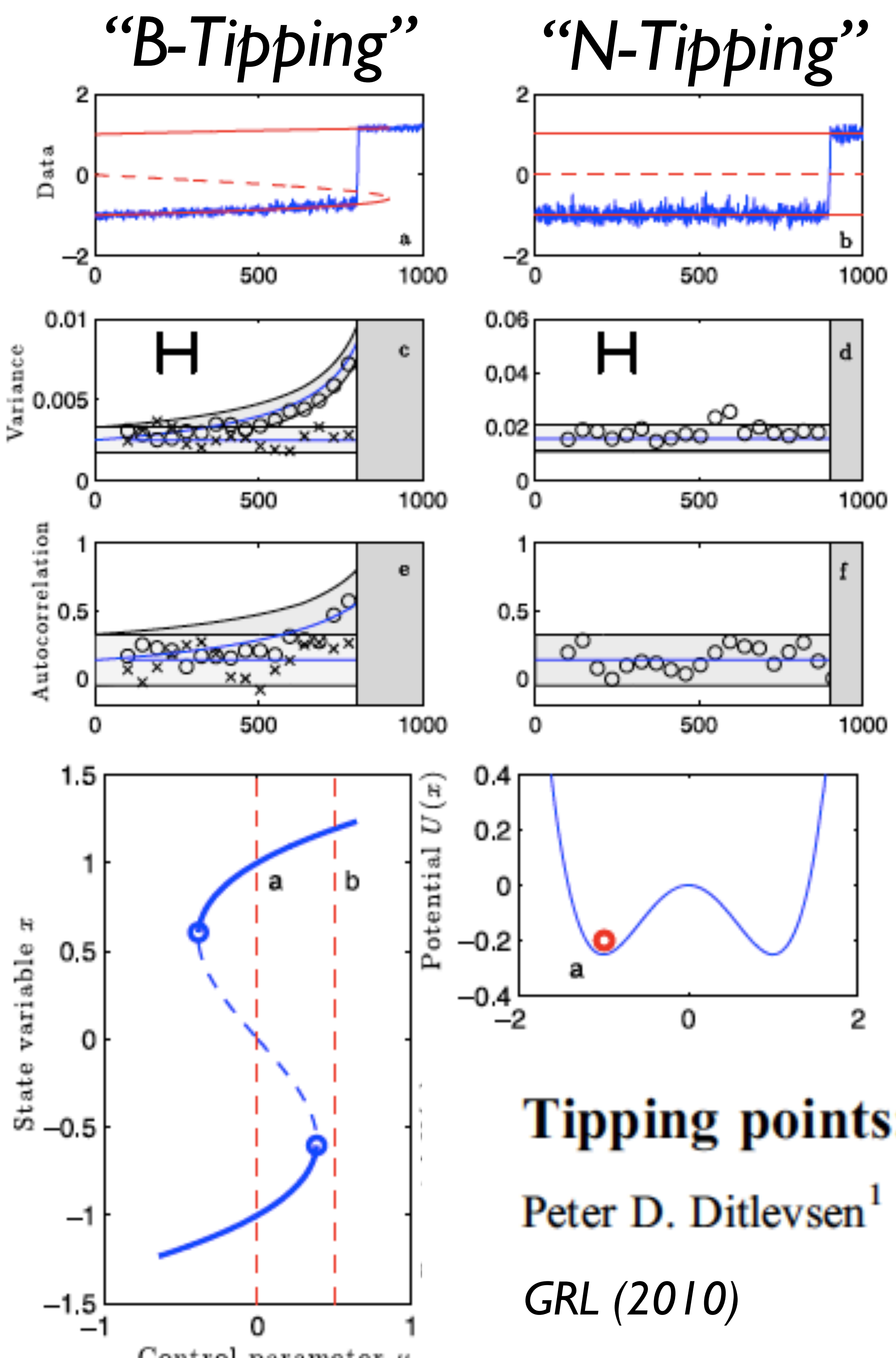
(Also, works of H.A. Dijkstra and collaborators)

Future directions:

What is a good signature of a bifurcation w.r.t. sea ice?



Disclaimer:tipping points, not always a bifurcation....



&"R-Tipping"

Ashwin, Wieczorek, Vitolo, Cox (2011)

Tipping points: Early warning and wishful thinking

Peter D. Ditlevsen[1] and Sigfus J. Johnsen[1]

GRL (2010)