# **Sea ice stability and early warning signals**

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### *Part 1*

# **Sea ice stability**

#### **Recent Arctic sea ice retreat**



• Arctic summer sea ice extent diminished by 45% during 36-yr satellite era (1979-2014).

#### **Ice-albedo feedback**

• The difference in albedo between ice and ocean causes a **positive feedback.** 

• According to satellite measurements, sea ice retreat caused the solar energy input into the Arctic to increase by  $6.4 \pm 0.9$  Wm<sup>-2</sup> during 1979-2011.

• Contribution to global energy budget is **25% as large as the direct radiative forcing from rising**  $CO_2$  **(0.2Wm<sup>-2</sup>).** *O.8Wm<sup>-2</sup>).* 

**Sept 2012** Sea Ice Cover and Change In Albedo

**Sept 1979** Sea loe Cover

**Pistone, Eisenman, & Ramanathan (2014)** 



darker no chan

> *Image credit: Collaboration with NASA Scientific Visualization Studio*

#### **Instability from the ice-albedo feedback: early history**



James Croll (1821-1890) 

• Croll (1875) was first to identify the importance of ice albedo as a positive feedback (in context of glacial cycles).

> • Brooks (1926) argued that the ice-albedo feedback would allow two stable climate states: one with little ice, another with a vast white polar ice cap.



*C.* **14:.** P. **Brooks.** *[M. Mnrti#z Photograph b.~]*  C.E.P. Brooks (1888-1957) 



Mikhail Budyko (1920-2001) 

• Budyko (1966) used an energy budget estimate to argue that if the sea ice were removed from the Arctic today then it would not return due to the ice-albedo feedback.

#### **Models of ice albedo and climate**



#### **Energy Balance Models (EBMs)**

- Most classic type of global climate model (Budyko 1969, Sellers 1969).
- Albedo depends on *T*. Heat transport as  $D\nabla^2T$ .
- Resulting  $T(x)$  agrees with observations.



• **Simulates instability and hysteresis during sea ice retreat** (Budyko 1969; Held & Suarez 1974; Lindzen & Farrell 1977; Suarez & Held 1979; North 1975ab, 1981, 1984, 1991; Winton 2008; Rose & Marshall 2009).



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#### **Models of ice albedo and climate**



### **Single Column Models (SCMs)**

- Classic method to study Arctic sea ice (Maykut & Untersteiner 1971).
- Includes seasonal cycle and sea ice thermodynamic processes.
- Resulting  $T(t)$  &  $h(t)$  agree with observations.



#### • Also simulates instability and hysteresis during sea ice retreat

(Thorndike 1992; Flato and Brown 1996; Björk 2002; Eisenman 2007, 2012; Eisenman and Wettlaufer 2009; Müller-Stoffels and Wackerbauer 2011, 2012; Abbot et al. 2011; Moon and Wettlaufer 2011, 2012; Björk et al. 2013). **THORNDIKE: TOY MODEL OF SEA ICE GROWTH 9407** 





#### **Models of ice albedo and climate**



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#### **Comprehensive global climate models (GCMs)** [7] Separation of the dependence of the dependence of the departure o  $\mathbf{r}$ <br>the sea **p**<br>
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- State-of-the art climate models, including atmosphere, ocean, sea ice, and land surface.
- NCAR CCSM3 (a GCM) **does not simulates instability and hysteresis** when **CO2 increased** until all ice gone and then decreased back to starting point (Armour et al. 2011). similar to the treatment by Winton [2011] except that we S<br>
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un (<br>ta<br>iC<br>ti of-<br>C<br>ic ea<br><mark>ny</mark> e.<br>se when the sea is the sea in the Arctic Sea in the Arctic Sea in the Arctic Sea in the Arcti
	- Behavior is **strikingly linear** no hint of nonlinearity from ice-albedo feedback.



- Similar simulations with **other GCMs yield similar results** (e.g., Ridley et al. 2012; Li et al. 2013; cf. Ferreira et al. 2011). er<br>2; dk<br>Li a<br>et linear<br>Sing and the set of th<br>Single set of the set of th range of GCMs, and contains scenarios, and contained a set of Gregory scenarios, and containing  $\overline{G}$  $e^{i\theta}$  $\frac{1}{2}$
- Using less direct approaches, a range of GCMs were found not to show evidence of instability from the ice-albedo feedback (Winton 2006, 2008; Ridley et al. 2007; Tietsche et al. 2011).

#### **Question**

Idealized climate models find instability in the sea ice cover.

Comprehensive climate models do not.

*Why?* 

Do idealized models miss essential physics? Or do comprehensive GCMs get things wrong?



Construct an idealized model that contains the physics in both EBMs and SCMs: an "EBM-SCM" that simulates  $T(t,x)$ .



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#### **Model development: EBM**



$$
f_0 \equiv aS - [A + B(T - T_m)] + D\nabla_x^2 T + F_b
$$

$$
\begin{array}{ll}\n\text{Insolation:} & S(x) = S_0 - S_2 x^2 \\
\text{Co-albedo:} & a(x, T) = \n\begin{cases} \na_0 - a_2 x^2 & T > T_m \\
a_i & T \le T_m\n\end{cases}\n\end{array}
$$

Heat transport: 
$$
D\nabla_x^2 T = D\frac{\partial}{\partial x}\left[ (1 - x^2)\frac{\partial T}{\partial x} \right]
$$

#### Model development: *+ Seasonal cycle*



#### Model development: *+ SCM physics*



#### **Model development: Numerical solution**



• At each timestep,  $T_0$  is solution of a nonlinear ODE involving  $\nabla^2T$  and a free boundary between melting and freezing ice surfaces.

• Rather than numerically solve this ODE at each timestep, we constructed an analogous twolayer system:

- Diffusion occurs in "ghost layer" (Implicit Euler time stepping).
- All other processes occur in main layer (Forward Euler time stepping).
- Energy exchanged between layers to relax ghost layer temp toward main layer.
- Two-layer system is equivalent to physical model in limit of fast relaxation time.

#### Default model run



- With  $F = 0$ , spun-up model state agrees reasonably well with observed current climate.
	- Ice edge migrates seasonally between 60°N and 80°N, with thick multiyear ice and thin seasonal ice.
- Simulated equilibrium model state is fully determined by spun-up  $E(x,t)$  during 1 year.



#### **Test for hysteresis**

• Sea ice retreat is approximately linear when F is ramped up.



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- Sea ice retreat is approximately linear when F is ramped up.
- Ramping F back down causes ice to recover along identical trajectory.
- $\triangleright$  No instability during sea ice retreat in this model!



#### **Test for hysteresis**

- Sea ice retreat is approximately linear when F is ramped up.
- Ramping F back down causes ice to recover along identical trajectory.
- $\triangleright$  No instability during sea ice retreat in this model!
- This EBM-SCM resembles a GCM rather than an EBM or SCM.



#### **Reduction to earlier models**

$$
S(t, x) = S_0 - S_2 x^2 - S_1 x \cos \omega t
$$

• Model reduces to **standard** *t***-independent EBM** when  $S<sub>I</sub> = 0$  [steady-state  $T(x)$  no longer depends on ice physics]: instability.  $\cdot$ *Fw*



$$
f_0 \equiv aS - [A + B(T - T_m)] + \lambda \nabla_x^2 T + F_b
$$

• Model reduces to standard *x*-independent SCM when  $D = 0$  (no horizontal communication between  $T(t)$  in each column): instability.  $\frac{1}{2}$   $\frac{1}{2}$ 

0.2

inst<u>ability</u>

#### Exploring parameter space  $(D, S)$ 1

 $\overline{\mathbf{u}}$  control

 $\cdot$  2

Run model with  $\begin{array}{c} \bullet 21 \text{ values of } S_1 \text{ in } [0, S_1^*] \\ \bullet 21 \text{ values of } D \text{ in } [0, D^*] \end{array}$  441 hysteresis loop simulations. • 21 values of  $D$  in  $[0, D^*]$  $\cdot$ *∆F Fc*



#### **Exploring parameter space**  $(D, S_1)$



 $\triangleright$  Meridional communication and seasonal cycle in solar forcing each increase stability.



#### **Behavior at origin**



• Albedo jump causes multiple states.



• Can visualize as "wells" of potential (U):

$$
\frac{dT}{dt} = -\frac{dU}{dT}
$$





#### **Dependence on seasonal cycle**

- Consider SCM regime  $(D = 0)$ .
- 85 *F* (W/m2 (cf. Eisenman 2012). need numerical solution for ice thickness • Nearly analytical solution for  $\Delta F(S_1)$  – just
- Increasing seasonal amplitude reduces  $\Delta F$ .
- potential wells, making it more difficult to easier to spontaneously jump between two • Conceptually, seasonal variations make it support bistability.







#### **Dependence on horizontal transport**

- Consider EBM regime  $(S<sub>1</sub> = 0)$ .
- $\Delta F(D)$  can be found analytically (cf. Lindzen and Farrell 1977; North 1984).
- • Increasing horizontal diffusivity reduces *∆F*, i.e., increases stability.
- Conceptually, diffusion smoothes out bistability of potential well, making it more difficult to support bistability.







#### **Dependence on horizontal transport**



#### **Putting it all together:**  $\Delta F(D, S_1)$



Expect that  $\Delta F(D, S_1) \approx \Delta F(0, S_1) + \Delta F(D, 0)$ 

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#### **Putting it all together:**  $\Delta F(D, S_1)$





#### **Summary of Part 1**

• Why do low-order idealized models simulate instability in the sea ice cover while comprehensive GCMs do not?

• Because idealized models have typically **neglected either seasonal variations or meridional heat transport**, and both have strong stabilizing effects.

• Including both  $S<sub>1</sub>$  and D causes ice cover to be stable.

**▶ The sea ice cover may be substantially more stable than has been suggested** in previous studies that used EBMs or SCMs.

• May be relevant to other cases with bistability only in low-order climate models.

Further details: Wagner & Eisenman, J. Climate 2015

Model code: **http://eisenman.ucsd.edu** 

## *Part 2*

# **Early warning signals**

#### **Early warning of approaching bifurcations**

• A flurry of recent studies have investigated **early warning signals** to **identify an** approaching bifurcation before it is reached.

• The **White House** has considered using **geoengineering** to avoid crossing climate tipping points (Associated Press, 2009).

#### Early warning signals: critical slowing down (1/2)



• As a bifurcation is approached in a simple dynamic system, the **potential well** becomes less steep.

## Early warning signals: critical slowing down (2/2)



• In a system subject to noise, this causes larger autocorrelation (i.e., slower recovery time) and **often larger variance:** "critical slowing down" warns of approaching bifurcation.  $\cdot$   $\cdot$  In s that allow recovery from local damage may set /stem subject to noise, this causes l**arger autocorrelation** (i.e., slower recover<sub>)</sub> down may be measured in stochastically induced fluctuations in the system (D and F) as  $\alpha$ 

**Autocorrelation is the leading candidate** to act as an early warning indicator.

#### **Previous studies of early warning signal**

• Autocorrelation has been proposed as an early warning signal of an approaching bifurcation in a wide range of systems (e.g., Scheffer et al. 2009, Scheffer et al. 2012).

• This has been examined in paleoproxy time series and climate models (e.g., Dakos et al. 2008, Lenton et al. 2012), modern satellite observations (e.g., Livina & Lenton 2013), financial markets (e.g., Hong & Stein 2003), ecosystems (e.g., Carpenter & Brock 2006), etc...



## **Question**



• From Part 1: This model gets no bifurcation when warmed from modern conditions, but cooling leads to snowball earth bifurcation.







• Begin with model described in Part 1.





- Begin with model described in Part 1.
- Add (weather) noise.





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*(Deal with complications associated with numerical integration...)* 





- Begin with model described in Part 1.
- Add (weather) noise.

*(Deal with complications associated with numerical integration...)* 



- Compute 10,000 realizations of noisy warming and cooling (varying *F*).
- Focus on September sea ice area.

# **Results: Cooling to Snowball earth**



• Climate cools until bifurcation, then **abruptly** jumps to Snowball earth.

• Lag-1yr **autocorrelation increases**. (Variance also increases). 

 $\triangleright$  Critical slowing down **correctly warns** of approaching Snowball earth bifurcation.

# **Results: Warming to ice-free earth**



• Ice declines smoothly, with no acceleration or abrupt loss.

• Lag-1yr **autocorrelation increases**. (Variance, however, decreases.) 

#### $\triangleright$  Critical slowing down raises a **false alarm!**

It warns of a bifurcation that is not actually there.

#### False alarm mechanism: Temperature at pole  $\ddot{\cdot}$ *(a) September Arctic sea ice area, Ai, versus climate forcing, F, and time, t (indicated*  -15 -10 -5 0 5 10 *Tp, and CSD indicators. As in*  0 -300 -200 -100 0 100 200 **Derature at p**



#### **False alarm mechanism: Simplified model**



• Part 1 results suggest that seasonal variations and heat transport act to reduce the effect of nonlinearity from albedo changes.

**Examoving transport & seasonal cycle** while using **constant albedo** may *plausibly* have compensating effects, with results qualitatively unaffected.

$$
\frac{\partial E}{\partial t} = a_0 \overline{S} - (A + BT) + F_b + F + N = \alpha - BT + N
$$
  
solar OLR ocean climate noise

• In this simplified system, influence of sea ice thermodynamics can be crudely approximated as a **change in effective heat capacity**:

$$
c(T)\frac{\partial T}{\partial t} = \alpha - BT + N \qquad c(T) \equiv \begin{cases} c_w/5 & T < 0 \\ c_w & T > 0 \end{cases}
$$

• This system represents an Ornstein-Uhlenbeck process (analytically solvable).

#### False alarm mechanism: Simplified model results **2. THEORY: JUMP IN HEAT CAPACITY AND RISING AUTOCORRELATION** fied model res **falsely predict abrupt sea ice loss** echanism: Simblined model results compensating effects, with results qualitatively unaffected. With *we show that a leading candidate to act as an early warning signal — rising autocorrelation [2] — can raise false alarms in the climate system, warning of tipping points that are not actually there.* fied model res Meridional heat transport and seasonal variations act to essentially remove the effect of nonlinearity from albedo changes echanism: Simp ied model resu We take *c* = *n* mechanism: Simplified model results 22 22.5 23 23.5 24 24.5 25 -2 **Inclear alguns use objections** Cinem<sup>pl</sup> Capacity <u>raise aldrin mechanism: simplified mode</u>  $\overline{d}$



**MODEL: SEA ICE AREA AND CRITICAL SLOW DOWN (CSD) I**o The re **a** *s*<sup>0</sup> *a s*<sup>0</sup> *i*</sup> *i p*<sup>m</sup> is *a i i o**a***</u>** *i**i**o**a**i***</del>** *i**o**a**i**i**d**a**i**i**d**a**j**a**j**a**j**a**j**a**j**a**j**a**j**a**j**a**j**a**j**a**j**a**j**a* **Snowball Earth**  • The simplified model rea resemble the full mode  $\overline{1}$ **The simplified model**  $\mathsf{essemble}\ \mathsf{the}\ \mathsf{?}$  $\overline{ }$ resemble the full model. • The simplified model results

vava v **THEORY — JUMP IN HEAT CAPACITY: Capacity** when sea ice is replaced  $-15$  -10  $-10$   $-10$ 0  $\cdot$  Suggeste simple a autocorrelatio the *increase* in with open ocean caus (while the variance decreases 0.79  $\mathbf{v}$  is motivated by the relaxation timescale of a single-column timescale of a single-column timescale of a single-column timescale of  $\mathbf{v}$ **Exangle is the seal ice is replaced** . I :he **increa** • Suggests simple explanation αι while the varian <u>aaloocii cidti</u>  $\bullet$ l, 5 **capacity** when sea ice is replace -15 -10 -5 10 10 warming autocorrelation to *(a) September Arctic sea ice area, Ai, versus climate forcing, F, and time, t (indicated along top of axes). Five realizations of warming and cooling are shown (faint red and*  th open ocean **cause iuggests simple** capacity when sea ice is replaced 7 the **increase in effective heat** 0.76 0.77 *Temperature and CSD indicators for a simple model undergoing cooling with varying*  0.78 with open ocean **causes** • Suggests simple explanation: (while the variance decreases). autocorrelation to increase

• No bifurcation or abrupt change occurs. *blue). (b) Variance of the time series in (a), computed using a 100 year running window*  0.78 0.8 *ice-free in September. (c) As in (b) but for lag-1 yr autocorrelation.* F (Wm-2) 0 change occurs. , no bifurcation or abrupt <mark>v</mark> *blue), as well as warming and cooling simulations with no added noise (dark red and*  • No bifurcation or abrupt



<sup>22</sup> 22.5 <sup>23</sup> 23.5 <sup>24</sup> 24.5 <sup>25</sup> 0.3

0.7

*Uhlenbeck process, when T<0 and T>0.*

**increase while the variance decreases.**

 $\frac{20!}{1}$ 

<sup>22</sup> 22.5 <sup>23</sup> 23.5 <sup>24</sup> 24.5 <sup>25</sup> 0.3

above is **not** indicative of an approaching bifurcation.

<sup>22</sup> 22.5 <sup>23</sup> 23.5 <sup>24</sup> 24.5 <sup>25</sup> <sup>0</sup>

<sup>22</sup> 22.5 <sup>23</sup> 23.5 <sup>24</sup> 24.5 <sup>25</sup> 0.3 *(a) One realization of the stochastic warming simulation (faint red), as well as the noisefree solution (dashed). (b) Variance and (c) autocorrelation, respectively, as in previous figures. The dashed lines in (b) and (c) show analytic solutions for this linear Ornstein-*

The evolution of σ2 and ρ resemble the full model (left), suggesting a physical explanation for the mixed Early Warning Signal behavior: **the increase in effective heat capacity when sea ice is replaced with open ocean causes the autocorrelation to** 

This could trigger a false alarm: the rising autocorrelation observed

#### Take home message: don't extrapolate





#### **Summary of Part 2**

• Rising autocorrelation is the leading candidate to act as an early warning signal for abrupt change.

• Our model has no abrupt sea ice loss, but the autocorrelation nonetheless increases during warming.

• This slowing down appears to be due to a **change in the effective heat capacity** from *ice-covered* (fast response) to *open water* (slow response).

• **Early warning signals can raise false alarms** during sea ice retreat, warning of bifurcations that are not actually there.

Further details: Wagner & Eisenman, GRL 2015

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• Why do low-order idealized models simulate instability in the sea ice cover while comprehensive GCMs do not?

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