Climate Tipping Points: Can they trigger a Global Cascade?

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EGU Session: **ITS3.1/NP1.2 Tipping Points in the Earth System** - 6/5/20

Background: ERA Project

- Postdoc on ERC-funded **Earth Resilience in the Anthropocene (ERA)** project @ Stockholm Resilience Centre (PI: Johan Rockström)
  - Focus: Mapping & modelling **nonlinear climate-biosphere interactions, feedbacks, & tipping points** that might commit us to 2+°C
  - **Key Q**: *How do changes in ecosystem dynamics modulate the strength & interactions of eco-climate feedbacks?*

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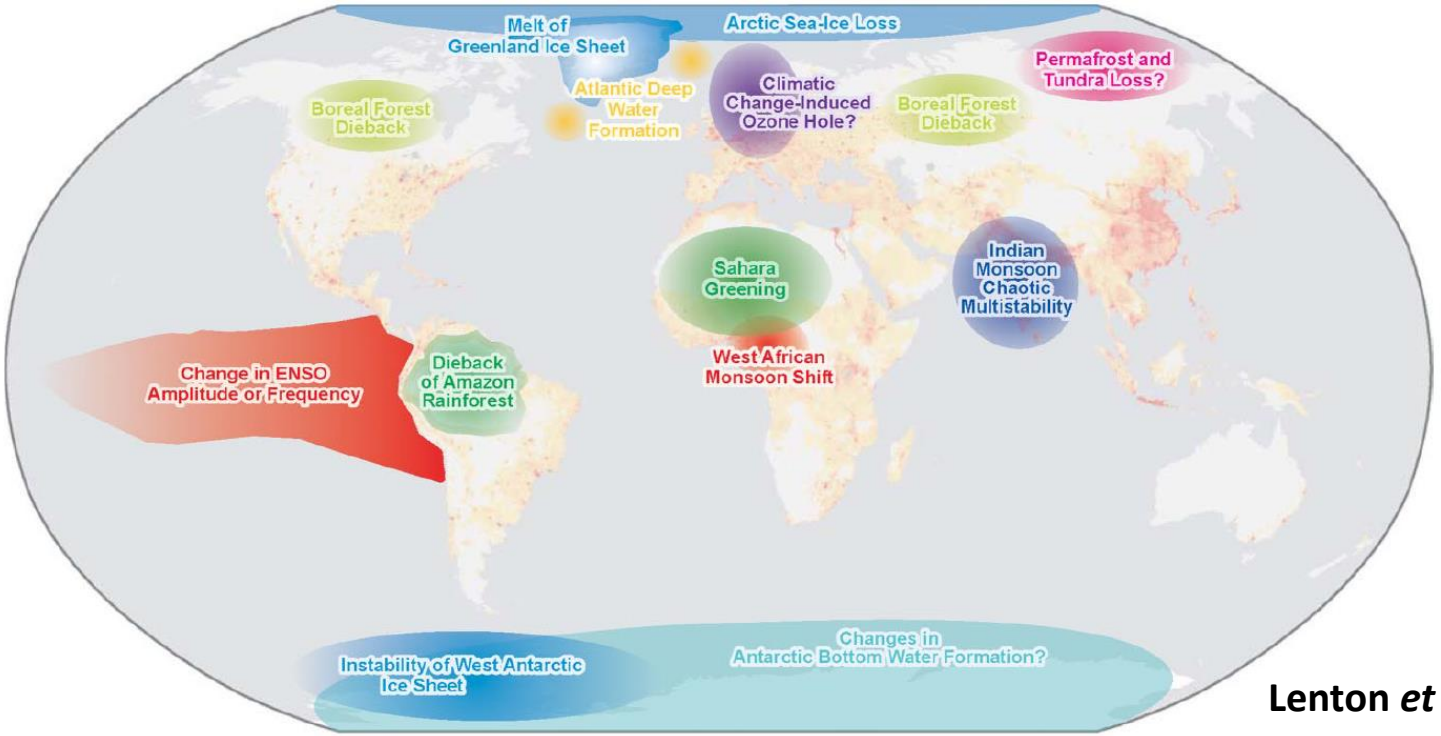
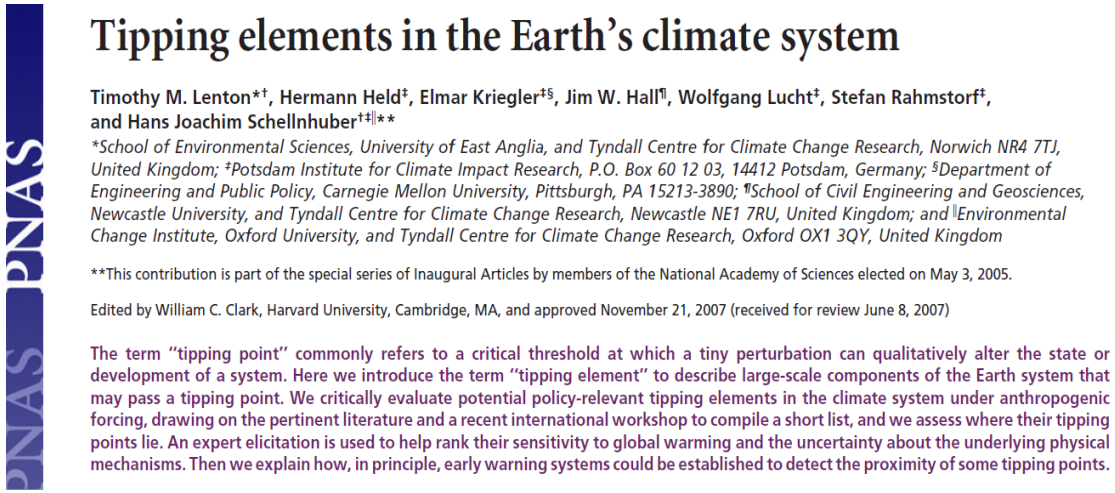
Study Aims

- **Original Study Aims**:
  - **Perform an updated systematic review** of climate tipping points, cataloguing the current evidence for each incorporating recent results from models and palaeoclimate studies
  - **Outline & rigorously apply a TiP definition** to differentiate catalogued TiPs from forced abrupt events or threshold-free positive feedbacks
  - Use estimates to develop a **stylised model** to **test potential for a global tipping cascade**
- **Current Situation:**
  - A systematic review of climate tipping points from another team is now under open review at Earth System Dynamics [Wang & Hausfather, 2020] – **a similar review now redundant?**
  - **New plan**: re-pivot to **model-focus** using updated estimates
- **Here we discuss evolution of the TiP Framework, updated TiP estimates, & present preliminary model results for TiP interactions**

Past Tipping Point Characterisations

- Over the past ~15 years **climate tipping points (TiPs) have emerged as an important research topic** and source of public concern
- '*The term ''tipping point'' commonly refers to a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system*'
- **Field catalysed by the expert elicitation & review of Lenton *et al* [2008]** (L2008)
- L2008 foundational for subsequent characterisations, and **for some TiPs is still the key citation**





PNAS

Tipping elements in the Earth's climate system

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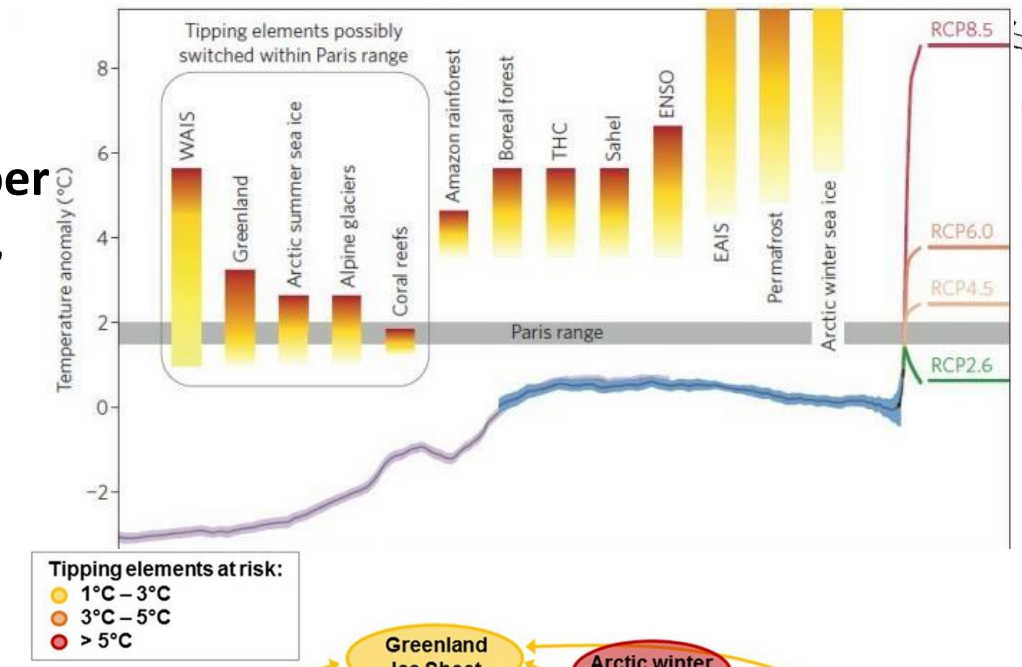
The term ''tipping point'' commonly refers to a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system. Here we introduce the term ''tipping element'' to describe large-scale components of the Earth system that may pass a tipping point. We critically evaluate potential policy-relevant tipping elements in the climate system under anthropogenic forcing, drawing on the pertinent literature and a recent international workshop to compile a short list, and we assess where their tipping points lie. An expert elicitation is used to help rank their sensitivity to global warming and the uncertainty about the underlying physical mechanisms. Then we explain how, in principle, early warning systems could be established to detect the proximity of some tipping points.

Lenton *et al*, 2008, PNAS

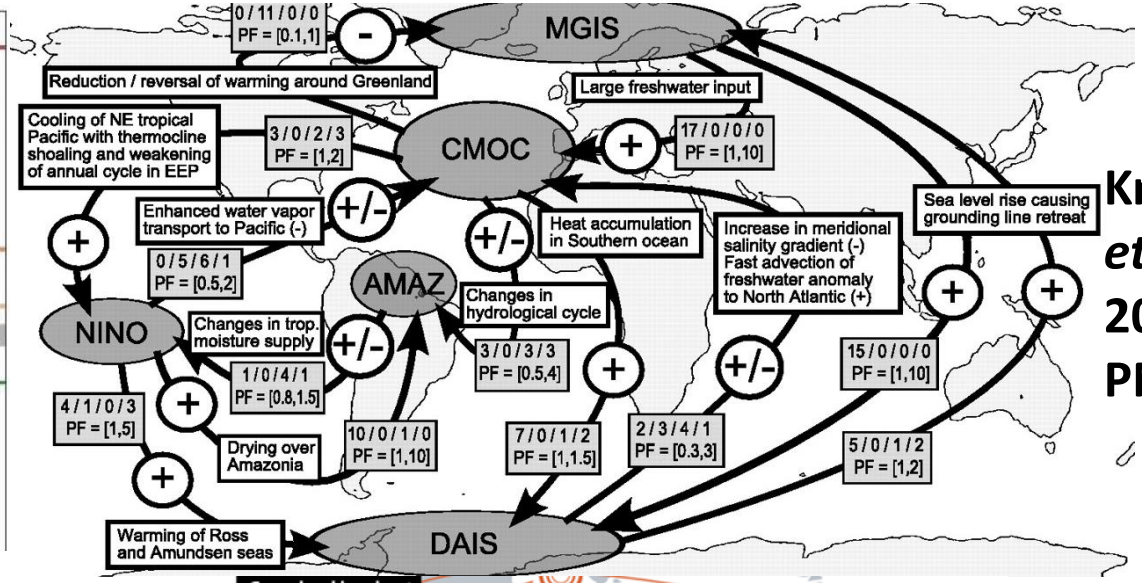
Past Tipping Point Characterisations

- More TiPs & possible teleconnections since added to this **'TiP Elements Framework':**

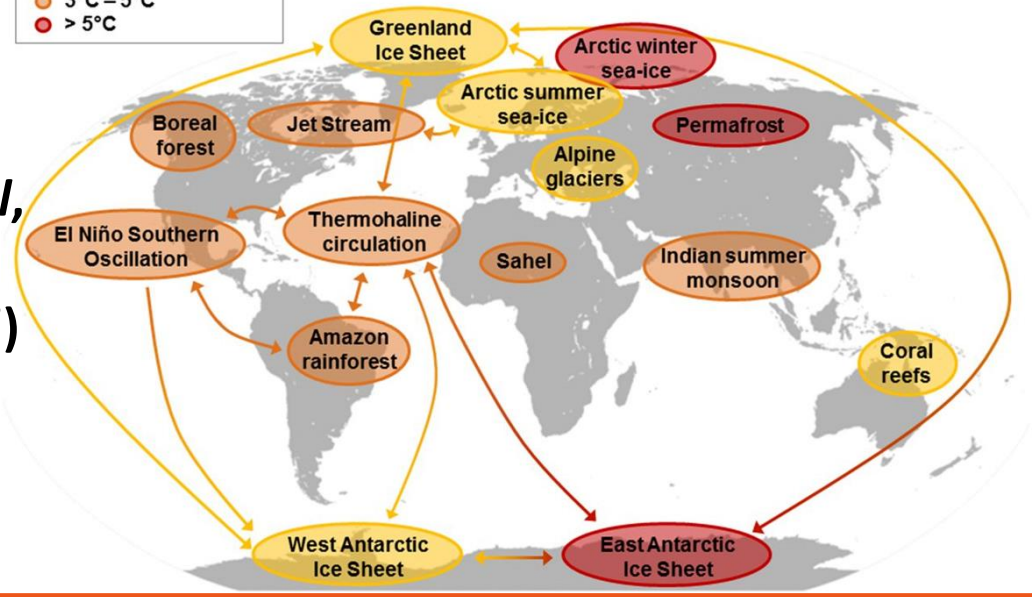
Schellnhuber *et al*, 2016, NatCC



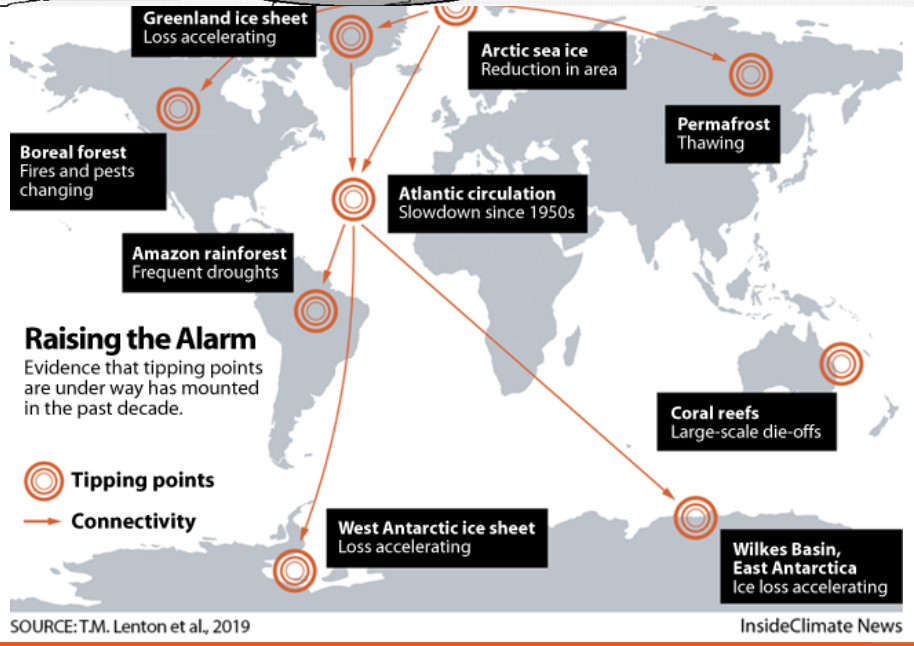
Kriegler *et al*, 2009, PNAS



Steffen *et al*, 2018, PNAS ('Hothouse')



Lenton *et al*, 2019, Nature ('L2019')



Past Tipping Point Characterisations

- **IPCC AR5 focused on 'Abrupt Events' – often equivalent to TiPs**, but not if simply a response to abrupt forcing or no self-perpetuation independent of forcing
- **Drijfhout *et al* [2015]** catalogued **Abrupt Events (AEs) in** CMIP5 (colours=warming proximity):

Abrupt Event (AE)	Temperature Threshold (°C) the AE Occurs at:				No. CMIP5 Models AE found in:
	Average all RCPs	In RCP8p5	In RCP4p5	In RCP2p6	
Sou. Ocean sea ice bimodality	2.9	4.7	2.1		1
Ind. Ocean upwelling change	10.9	10.9			1
Arctic winter sea ice collapse	6.3	6.3			5
Barents abrupt sea ice loss	1.6	1.6			2
SO abrupt sea ice loss	2.1	2.6	1.9	1.4	4
SO abrupt sea ice increase	1.6		1.6		1
Labrador convection collapse	1.9	3.8	1.6	1.5	5
AMOC collapse	1.6	1.9	1.6	1.4	1
Permafrost collapse	5.6	5.6			1
Tibetan snow melt	1.8	2	1.7		2
Sahel vegetation changes	2.8	3.5	2.8	2.1	1
Boreal forest expansion	7.2	7.2			1
Amazon forest dieback	2.5	4.4 (2.5-6.2)			2

Drijfhout *et al,* 2015, PNAS

Past Tipping Point Characterisations

- **TiP Elements Framework evolution** (L2008->L2019) **& AEs** (colour=proximity):

Tipping Element	Lenton et al 2008			Schellnhuber et al 2016			Steffen et al 2018			Lenton et al 2019			Drijfhout et al 2015: CMIP5		
	Thresh.	Time.	Impact	Thresh.	Time.	Impact	Thresh.	Time.	Impact	Thresh.	Time.	Impact	Thresh.	Time.	Impact
Arctic Summer Sea Ice (ASSI)	0.5-2	10	+	1-2.6			1-3		+	2<	-	+ reg	Rapid ice melt feedbacks not well represented		
Greenland Ice Sheets (GIS)	1-2	>300	<	1-3.2			1-3		+	1.5	1k-10k				
Marine-based Antarctic Ice Sheets (MAIS)	3-5	>300	<	1-5.6			1-3		+	1-1.5	100s-1ks				
Atlantic Thermohaline Circulation (THC)	3-5	100	- reg	3.5-5.6			3-5		+/-reg?			+/- reg	*1.63**	50	-4 reg
Amazon Forest Dieback (AFD)	3-4	50	<	3.5-4.6			3-5		+.05@2C			+	2.5-6.2	150	
Boreal Forest Dieback (BFD)	3-5	50	<	3.5-5.6			3-5		+.06@2C			+	Limited veg. dynamics		
Arctic Permafrost Thaw (APFT)	N/A	<100	+	4.8-9+			5+		+.1 @2C			+	5.60	50	
West African Monsoon (Sahel/Sahara)	3-5	10	<	3.5-5.6			3-5		<?				2.80	50	
Permanent El Nino (ENSO)	3-6	100	<	3.5-6.6			3-5		+(reg)?						
Coral Reefs				1.3-1.8?			1-3		<?	<2			Not represented		
East Antarctic Ice Sheet (EAIS)				4.5-9+			5+		+?						
Arctic Winter Sea Ice (AWSI)				5.5-9+			5+		+?				6.30	100	+ reg
Alpine glaciers				1-2.6			1-3		<?						
Jet Stream Instability (JSI)							3-5		<?						
Indian Summer Monsoon (ISM)	N/A	1	<				3-5		<?						

- Gradual expansion of ‘core’ TiPs
- Marine-based Ice Sheet threshold reduced from 3-5C to 1-1.5C (L2019)
- ‘Upgrade’ of Permafrost from gradual feedback to TiP

Past Tipping Point Characterisations

- **Increased focus on global warming feedbacks** & possible 'Tipping Cascade' in Steffen *et al* [2018] & L2019
- **Carbon focus in Steffen *et al* [2018]** – e.g. Boreal Forest Dieback as net positive feedback from carbon release, but models project net cooling from Boreal deforestation from albedo & other physical feedbacks [e.g. Bathiany *et al*, 2010]
- **Several core L2008->L2019 TiPs were not well resolved by CMIP5 models,** e.g. ice sheet collapse or forest dieback – CMIP6 should resolve more
- **Several significant potential TiP candidates from CMIP5 have not been included in core framework**, e.g. Labrador Sea Convection Collapse, Tundra Afforestation

Climate Tipping Points Definition

- Climate tipping point **definitions are often inconsistent** – some TiPs can more accurately be represented as abruptly-forced events or threshold-free positive feedbacks
- **Our three-part climate tipping point definition** *(key aspects italicised)*:

"*Tipping points* occur when change within a forced system (the '*tipping element*') becomes:
(a) *self-perpetuating* independent of the original forcing after it passes
(b) a *critical threshold* in the original forcing (the 'point of no return') and results in
(c) a *regime shift* to a significantly new system state"

- A clearly-defined **self-perpetuation mechanism** (e.g. a feedback) is a key requirement – this often results in **irreversible/hysteretic behaviour**, but is not directly required
- A **critical threshold** leading to a **regime shift** differentiates from **threshold-free feedbacks** (e.g. Arctic Summer Sea-Ice) or **AEs**, & new state must be qualitatively/quantitatively different

Updated TiP Estimates & Knowledge Gaps

Proposed Tipping Element	Threshold Steffen *et al* 2018	Threshold this Review^
Arctic Summer Sea Ice (ASSI)	1-3	N/A [1.7 (1.3-2)**]
Greenland Ice Sheets (GRIS)	1-3	1.6 (0.8-3.2)**
Marine-based Antarctic Ice Sheets (MAIS)	1-3	1.6 (1.0-2.5)*
Atlantic Merid. Overturn. Circulation (AMOC)	3-5	5.0 (3.0-8.0)
Amazon Forest Dieback (AFDB)	3-5	4.0 (2.0-6.2)*
Boreal Forest Dieback (BFDB)	3-5	3.5 (3.0-5.0)
Arctic Permafrost Thaw (APFT)	5+	4.0 (3.0-6.0)*
West African Monsoon (WAM)	3-5	2.8 (2.1-3.5)
Permanent El Nino (ENSO)	3-5	? (3.0-6.0)
Coral Reefs	1-3	1.5 (1.0-2.0)**
East Antarctic land-based Ice Sheet (EAIS)	5+	7.0 (5.0-10.0)*
Arctic Winter Sea Ice (AWSI)	5+	6.3 (4.5-8.7)**
Alpine glaciers	1-3	2.0 (1.7-3.0)*
Jet Stream Instability (JSI)	3-5	? (3.0-5.0)
Indian Summer Monsoon (ISM)	3-5	? (2.0-5.0)
Marine Methane Hydrates	N/A	?
Marine Bio Pump Weakening	N/A	N/A*
Carbon Sink Weakening	N/A	N/A*

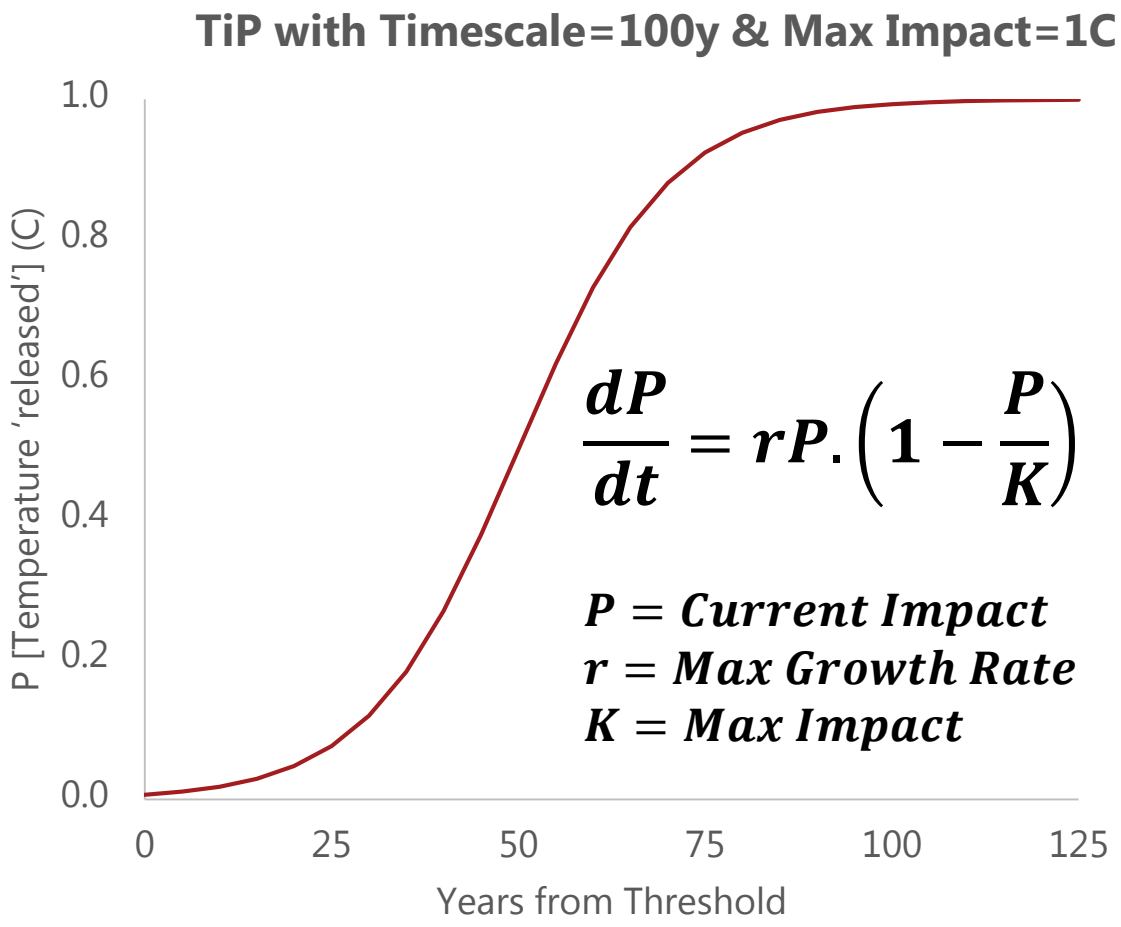
^Confidence: **=High, *=Medium, none=Low

- **Updated literature-based estimates** for TiP Thresholds (e.g. *left*), Timescales, & Impacts **broadly match Steffen *et al* [2018]**
- **Knowledge gaps:**
  - **Uncertain thresholds:** AMOC, BFDB, AFDB, APFT; & **global impacts:** AMOC, BFDB, GRIS, MAIS, EAIS
  - **Some very uncertain Elements**, e.g. Equatorial Cloud Breakup, Arctic Ozone Hole, Global Anoxia
  - Do **ENSO & Jet Stream** have **threshold behaviour?**
  - **Threshold-free Feedback strengths** (e.g. Carbon Sink Weakening) beyond 2100
  - **How many TiPs have significant 'Activation Times'** (i.e. how long do temperatures have to remain above threshold to trigger the TiP)?
  - How much do **non-temperature feedbacks reduce TiP thresholds** (e.g. GRIS->sea level->MAIS)?

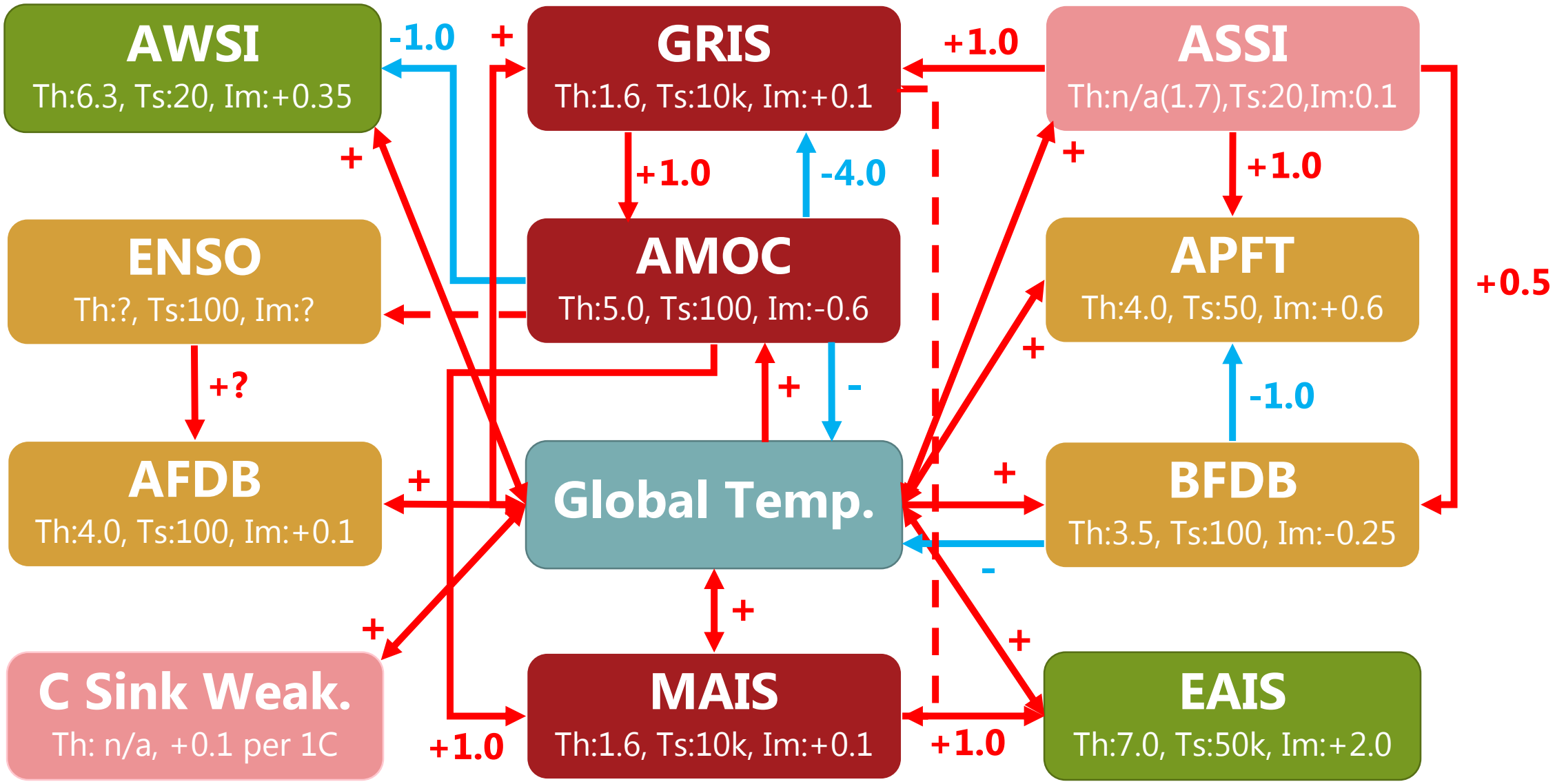
Stylised TiP Model: Design

- **Aim:** Use estimates to test **potential for global cascade** using a **stylised model**
  - *Does adding tipping points & their teleconnections to future projections lead to significantly amplified warming beyond 2C?*

- **System Dynamics Model** – ODEs for each TiP linked to global mean surface temp.
  - **Before** Threshold = **linear feedback on GMST** (saturating at max. impact)
  - **After** Threshold = **+ logistic function** (*right ->*) & once triggered keeps going
  - **Regional Feedbacks** for relevant TiPs (e.g. ASSI reduces APFT threshold – *see next slide*)
  - **Output** = GMST projection (extended RCP4p5 /8p5, GISS here as low feedbacks) + TiP Impacts
  - **Further development**: rate-dependent tipping, activation times, long-future inputs

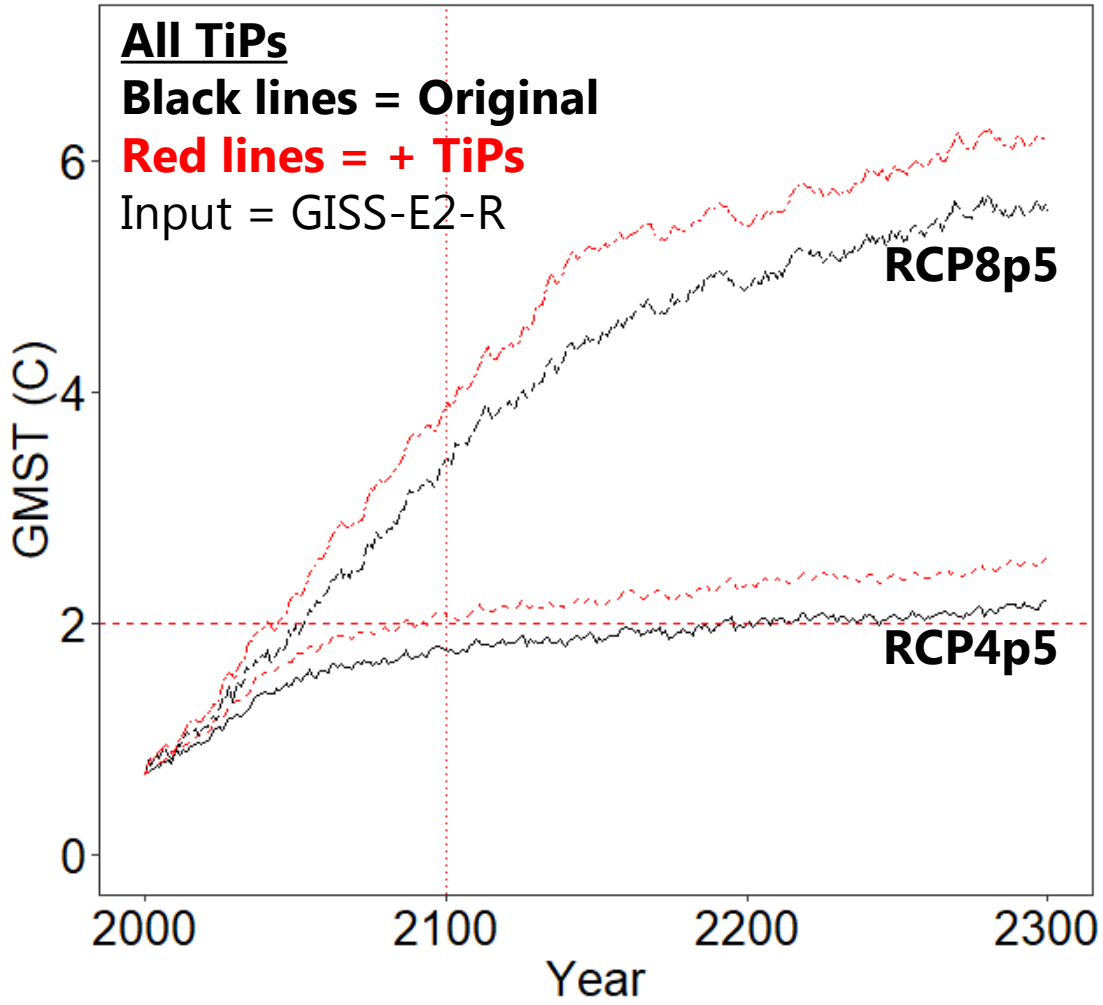


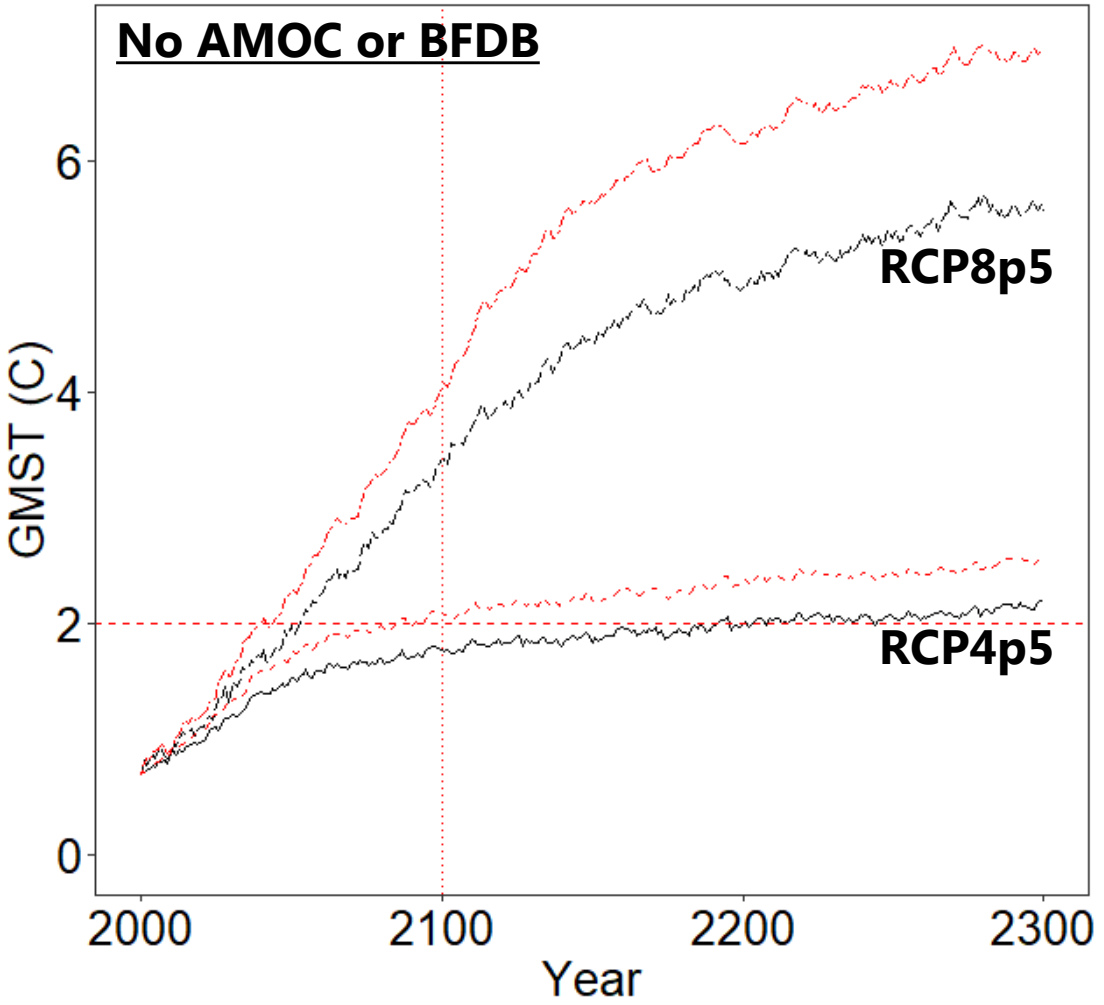
Stylised TiP Model: Design



Th=Threshold, Ts=Timescale, Im=Max. Global Impact, Box colours=warming proximity (pink=Th-free), Arrows=feedback

Stylised TiP Model: Preliminary Results





- **Moderate extra warming from TiPs** (*left*) of ~0.3C (4p5) to ~0.6C (8p5) by 2300
- **+TiP amplification** of ~0.4-1.3C (*right*) **partly offset by AMOC & BFDB cooling**
- **No cascade from 2->4C in RCP4p5** – further model dev. needed to explore

Summary

- We **catalogue past characterisations** of climate tipping points & abrupt events
- We **outline a three-part climate TiP definition** that differentiates TiPs from abruptly-forced events or threshold-free positive feedbacks
- We **update estimates for TiP categorisations, thresholds, timescales, & impacts**, and highlight **key knowledge gaps**
- We use these estimates to drive a **stylised Tipping Cascade model**, with preliminary results showing **moderate TiP amplification of future warming partly offset by net cooling effects of AMOC shutdown & Boreal Dieback**
- ***Postscript:*** *I'm looking for a new role from July – opportunity tip-offs welcome!*

Thank you for reading!

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