# Holocene stability: climate attractor, or lucky break?

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#### The Holocene in context

- Palæorecords indicate that global temperatures have been relatively stable for the past ~10,000 years of the Holocene epoch
- **Contrasts with cooling trends during previous interglacials**, forming G/IG "sawtooth" pattern, and **multiple abrupt shifts during past glacials**



# **Hypotheses for Holocene stability**

- Early emissions counteracted cooling [Ruddiman, 03; et al., 20]
- CO<sub>2</sub> rebound from lagged deglaciation feedbacks, e.g. CaCO<sub>3</sub> compensation [Broecker+ 99], Younger Dryas AMOC pause [Ganopolski & Brovkin, 17]
- Orbital quietude [Berger & Loutre, 02; Ganopolski et al., 16; Alvarez-Solas, EGU24]
- (Side note: Holocene 'stability' can itself be interrogated – it's stable as in low variability in global temperature, but masks larger regional changes, & low variability ≠ dynamical stability)



## **Hypotheses for Holocene stability**

- Alternative, grounded in dynamical systems: Holocene stability is function of being in an 'attractor', with strong negative feedbacks stabilising climate's state
- G/IG cycling therefore represents either a limit cycle or tipping between glacial and interglacial attractors





## From Holocene to Hothouse?

- This has led to the more recent hypothesis that human actions are **eroding the resilience of Earth system's current state** [Richardson et al., 23; Rockström et al., 24]
- Additionally, suggested that could be nearing tipping point of the whole Earth system into a warmer "Hothouse Earth" attractor [Steffen et al., 2018]
- Exit from stable(ish) Holocene part of case made for Anthropocene [e.g. Turner+24]



## **Evidence for climate attractors from deeper time**

- Several states diagnosed from Cenozoic to Phanerozoic palæorecords, in phase space [Foster & Rohling, 13] or by quasipotential / recurrence analysis [Westerhold+ 20; Boettner+ 21; Rousseau+23; Judd+ 24] (but, do all states = attractors?)
- And from models: EBMs e.g. Snowball Earth [Budyko 69]; PLASIM [Margazoglou et al., 19]; MITgcm [Ferreira+ 18; Brunetti+ 23, EGU24], inc. as Aquaplanet [Brunetti+ 19; Ragon+ 22]



#### **Evidence for Holocene & Hothouse attractors**

- Despite many hypotheses for Holocene stability, that the Earth system is close to the edge of an attractor is often assumed rather than demonstrated [e.g. Steffen+ 18; Rockstrom+ 21; 24; Kim 22; various media]
- Tipping points & feedbacks given as driver of warming drift from 2°C [Steffen et al., 18], but TPs at risk by ~2°C don't add lots of warming [A.McKay et al., 22; Wang et al., 23]
- Adding TPs to a simple model yields extra feedbacks, but no global threshold (or *"physical climate limit"*) to much warmer state emerges [A.McKay, in prep.]



• 1.5°C is a physical limit beyond which Earth systems enter a danger zone of cascading climate tipping points that propel further warming.



#### **Evidence for Holocene & Hothouse attractors**

- Models support general possibility of attractors, & palæorecord analysis identify candidates, e.g. Hot-, Warm-, Cool-, Icehouse, Snowball, plus dynamics shifts (e.g. Mid-Pleisto. intensification)
- Ice.→Coolhouse transition possible then (but, on track for Pliocene anyway), but palæo analyses
  don't differentiate bistable Glacials/Interglacials
- Interglacials / Holocene also explainable by several other hypotheses: excitation / limit cycle from glacial state [Saltzman+ 84+; Crucifix 12; Pierini 23]; lagged feedbacks & orbital quietude [ibid.]
- We need more evidence to compare these, & for whether palæo states exist for current conditions



## How else can we conceptualise Earth system resilience?

- In multi-stable picture, ES resilience = net
  -ve feedbacks keeping system in attractor,
  transitioning to net +ve at threshold
- ES resilience not tied to multi-stability -ve feedbacks may buffer from *any* initial state if rate stays within adaptive capacity; reflects a messier N-D stability landscape
- Resilience: Engineering (return to initial state) or Ecological (reorganise to maintain function) [Holling 73; 96]? Cf. dynamic turn in Ecology, & "resilience of what, to what"
- Related: what do we mean by ES state phase space of climate & biosphere?



### **Implications & Summary**

- Palæorecords & models support some climate attractors, but while near-term planetary tipping to a warmer attractor is possible, it remains speculative
- G/IG cycling & Holocene stability can be explained by other hypotheses (e.g. orbitally-paced excitations from glacial state; orbital quietude, lagged feedbacks)
- Earth system resilience can be conceptualised without attractors per se, and can also consider adaptiveness of ecological resilience
- Stating Holocene → Hothouse tipping point as known may help motivate action, but also carries risks, such as fatalism or risky interventions, and forecloses other ways of understanding future trajectory & Holocene difference to prior IGs
- Wider thought: should the ends of climate action (& object of governance) be managing for planetary stability? How do our framings affect wider discourse?

#### Thank you – any questions?

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