



2017年(第26回) ブループラネット賞
受賞者記念講演会

2017 Blue Planet Prize
Commemorative Lectures

ハンス・J・シェルンフーバー教授
講演スライド集

「 Out of the Ice, into the Fire? 」

Professor Hans J. Schellnhuber

Slides for the Lecture

“ Out of the Ice, into the Fire? ”

Blue Planet Prize 2017, Commemorative Lecture,
Tokyo, 19 October 2017

Out of the Ice – into the Fire?

Hans Joachim Schellnhuber

*Director, Potsdam Institute for Climate Impact Research;
Professor for Theoretical Physics, University of Potsdam;
Senior Research Fellow, Stockholm Resilience Centre*



How Many Earth-like Planets Are There?



Tens of Billions!

arXiv:1605.02825v1 [astro-ph.EP] 10 May 2016

DRAFT VERSION MAY 11, 2016
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FALSE POSITIVE PROBABILITIES FOR ALL KEPLER OBJECTS OF INTEREST: 1284 NEWLY VALIDATED PLANETS AND 428 LIKELY FALSE POSITIVES

TIMOTHY D. MORTON¹, STEPHEN T. BYRSON², JEFFREY L. COCCARDI³, JASON F. BOWE⁴, GANESH RAJACHANDRAN⁵,
EUSEBIO A. PEDERZA⁶, MICHAEL B. HAAS⁷, AND NATHAN M. BUTTRICK⁸

Draft version May 11, 2016

ABSTRACT

We present astrophysical false positive probability calculations for every Kepler Object of Interest (KOI)—the first large-scale demonstration of a fully automated transiting planet validation procedure. Out of 7056 KOIs, we determine that 1935 have probabilities <1% to be astrophysical false positives, and thus may be considered validated planets. 1284 of those have not yet been validated or confirmed by other methods. In addition, we identify 428 KOIs likely to be false positives that have not yet been identified as such, though some of these may be a result of unidentified transit timing variations. A side product of these calculations is full stellar property posterior samplings for every host star, modeled as single, binary, and triple systems. These calculations use *vepra*, a publicly available Python package able to be easily applied to any transiting exoplanet candidate.

1. INTRODUCTION

The Kepler mission has revolutionized our understanding of exoplanets. Among many other important discoveries, it has revealed a previously unsuspected abundance of small planets, such as the previously unknown population of rocky planets (e.g., Morton et al. 2013; Foreman-Mackey et al. 2014; Burke et al. 2015). It is important to remember, however, that these revolutionary discoveries depend intimately on another revolution—how to interpret transiting planet candidate signals in the absence of unambiguous positive confirmation of their veracity.

Before *Kepler*, every survey searching for transiting exoplanets demanded that a candidate signal be verified as a true planet via radial velocity (RV) measurement of its host star. This would involve a series of follow-up observations in order to weed out astrophysical false positive scenarios—typically stellar eclipsing binaries in various configurations. However, following this model has been largely impossible for *Kepler* because of the quantity and character of the planet candidates (thousands of newly small-planet candidates around relatively faint stars). There have been a small number of *Kepler* planets with masses measured by RVs (e.g., Marcy et al. 2014; Santerne et al. 2015), and significantly more that have been confirmed as planets by measurement of transit tim-

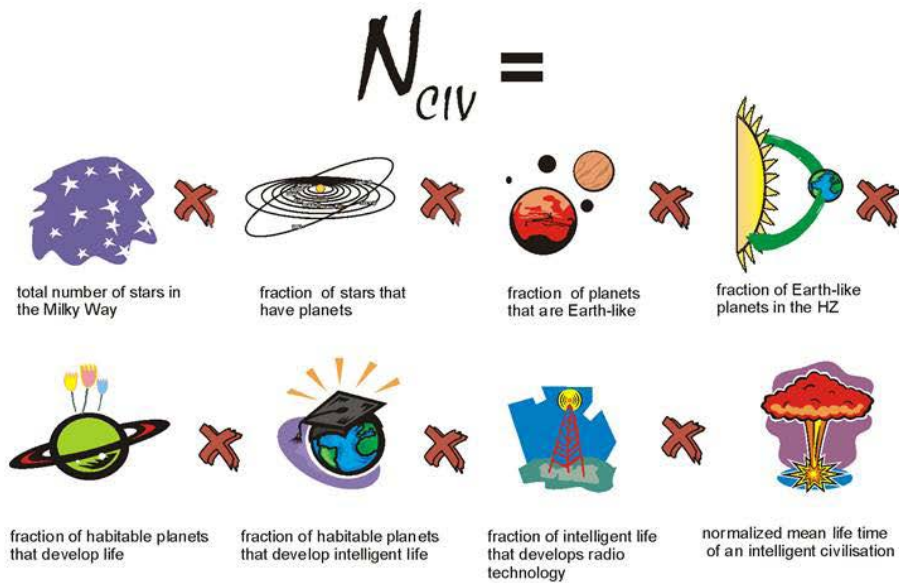
ing variations (TTVs) in multi-planet systems (e.g., Ford et al. 2012; Steffen et al. 2012; Fabrycky et al. 2012; Steffen et al. 2013; Jontof-Hutter et al. 2015), but this still leaves the vast majority of candidate transits unconfirmed.

This problem has inspired the development of probabilistic validation as a new approach to evaluating transit candidates. The principle of probabilistic validation is to assign a probability to all conceivable astrophysical false positive scenarios, and to weigh the probability of a transit candidate signal compared to the explanation of a planet transiting the presumed target star. The BLENDER method pioneered this approach and has validated many *Kepler* candidates (e.g., Borucki et al. 2012; Nipping et al. 2014; Torres et al. 2015). More recently, the PASTIS analysis suite has been introduced (Diaz et al. 2014) and used to validate both *Kepler* and *CoRoT* candidates (e.g., Santerne et al. 2014; Morton et al. 2014). An alternative validation approach for candidates in multiple-planet systems has also been applied to a large number of *Kepler* systems based on the general argument that it is unlikely to see multiple false-positive signals in the same *Kepler* light curve (Lissauer et al. 2012), resulting in validations of over 800 planets with 99% confidence (Lissauer et al. 2014; Howe et al. 2014). This methodology differs from the BLENDER/PASTIS approach in two significant ways: (a) it is applicable only to planets in multi-planet systems, and (b) it relies on broad-brush general arguments rather than analyzing the details of candidate signals individually.

While they have both proven useful for the purposes of validating individual candidates of particular interest, neither BLENDER nor PASTIS is designed for fully automated batch processing of large numbers of candidates. Morton (2012) describes a computationally simpler planet validation procedure designed for exactly such a purpose, based on the idea of describing eclipse light curves as simple trapezoids and simulating realistic populations of astrophysical false positives. This procedure has also been used in the literature to validate a number of *Kepler* planets (e.g., Mithod et al. 2012; Dawson et al. 2012; Seiff et al. 2013), and has also been

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⁶ California Institute of Technology, Pasadena, CA 91125, USA
⁷ Hubble Fellow

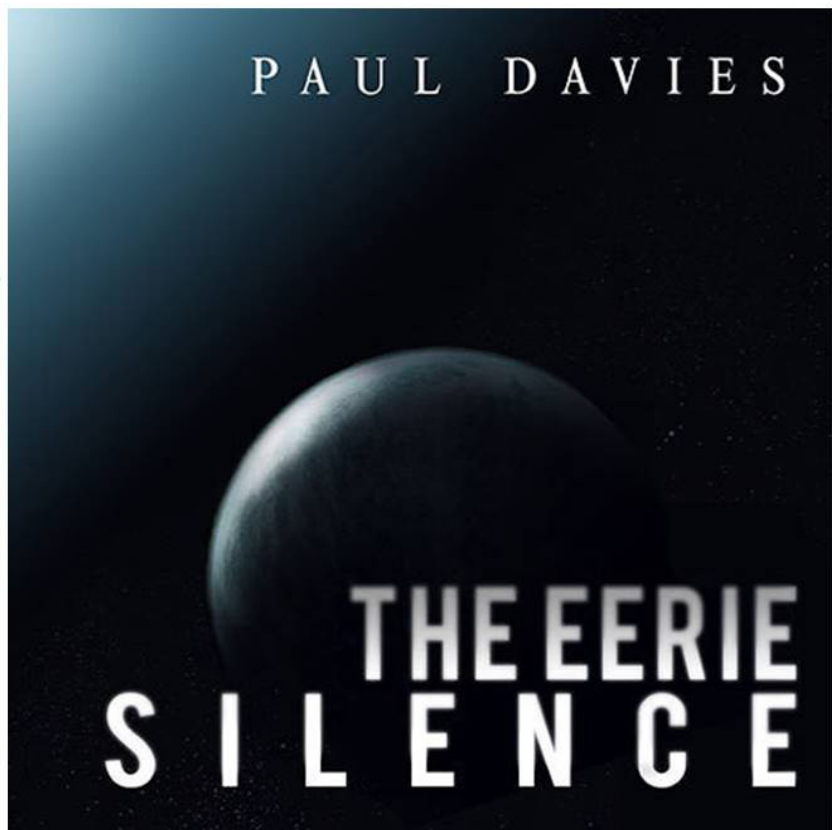
How Many Technical Civilizations Are There?



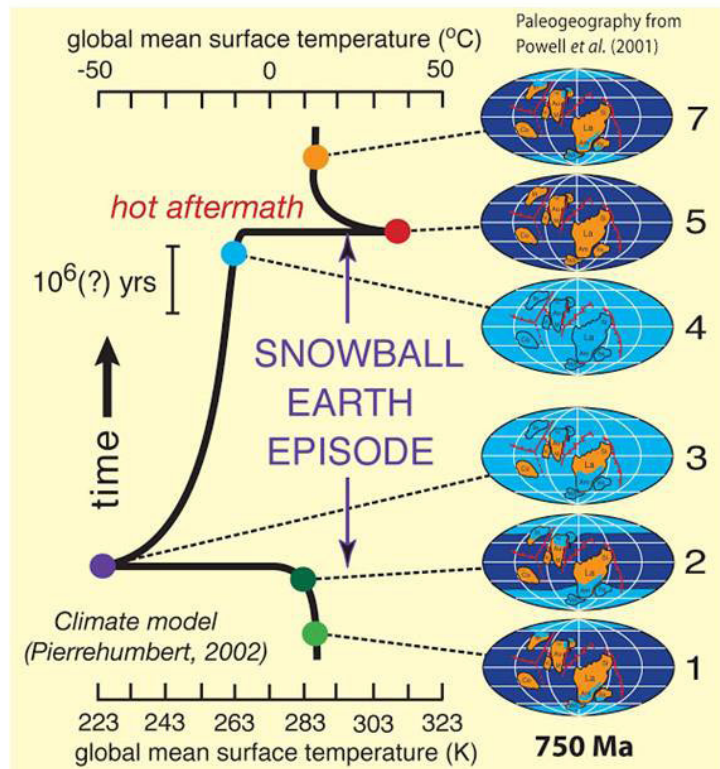
Drake's Equation

„It would be a tragedy of literally cosmic proportions if we succeeded in annihilating (...), the one truly intelligent species in the entire universe.“

Paul Davies,
NYT, 21 April 2010



Snowball Earth



Carboniferous/Permian: Creating Coal, Cooling Earth

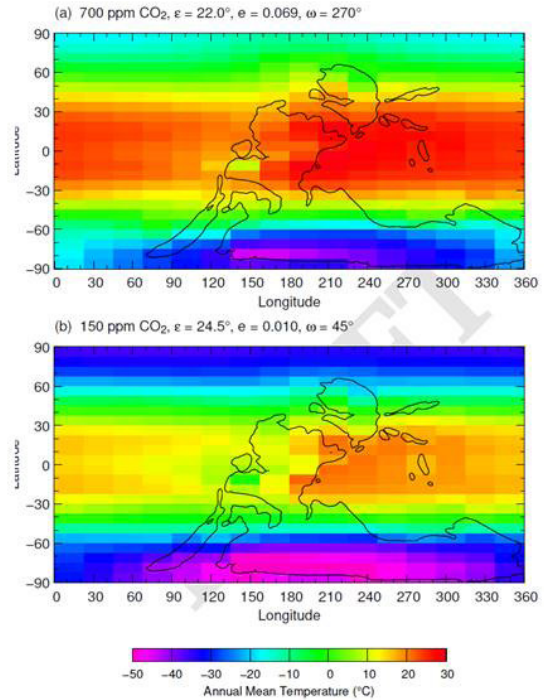
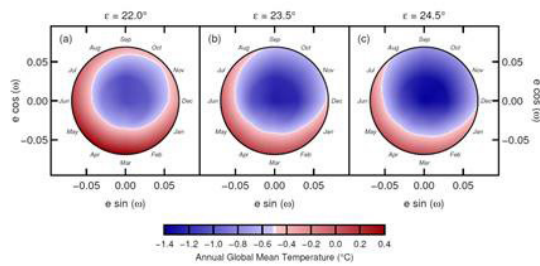
Formation of most of our coal brought Earth close to global glaciation

Georg Feulner¹

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Edited by Mark H. Thiemens, University of California, San Diego, La Jolla, CA, and approved September 5, 2017 (received for review July 7, 2017)

The bulk of Earth's coal deposits used as fossil fuel today was formed from plant debris during the late Carboniferous and early Permian periods. The high burial rate of organic carbon correlates with a significant drawdown of atmospheric carbon dioxide (CO₂) at that time. A recent analysis of a high-resolution record reveals large orbitally driven variations in atmospheric CO₂ concentration between ~150 and 700 ppm for the latest Carboniferous and very low values of 100 ± 30 ppm for the earliest Permian. Here, I explore the sensitivity of the climate around the Carboniferous/Permian boundary to changes in Earth's orbital parameters and in atmospheric CO₂ using a coupled climate model. The coldest orbital configurations are characterized by large axial tilt and small eccentricities of Earth's elliptical orbit, whereas the warmest configuration occurs at minimum tilt, maximum eccentricity, and a perihelion passage during Northern hemisphere spring. Global glaciation occurs at CO₂ concentrations < 40 ppm, suggesting a rather narrow escape from a fully glaciated Snowball Earth state given the low levels and large fluctuations of atmospheric CO₂. These findings highlight the importance of orbital cycles for the climate and carbon cycle during the late Paleozoic ice age and the climatic significance of the fossil carbon stored in Earth's coal deposits.



Feulner 2017, PNAS (accepted)

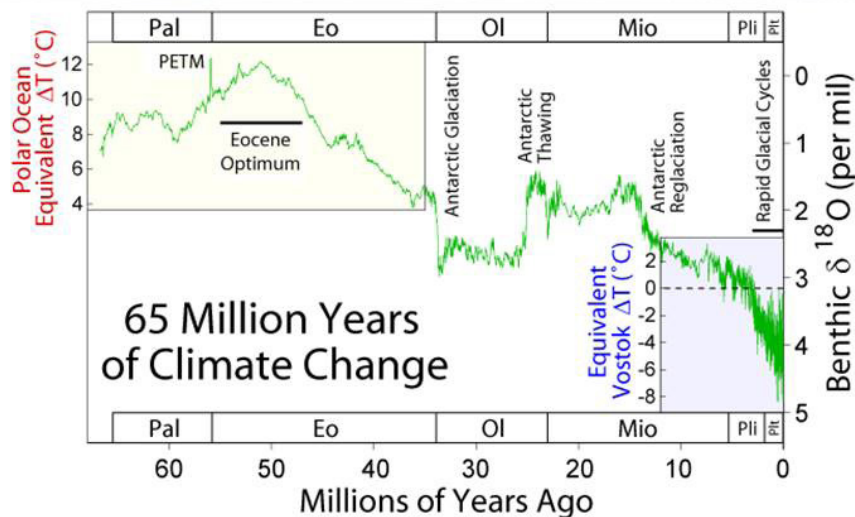
Carbon Levels ...

... a main dial in forming the Antarctic Ice Sheet in the past

... and triggering a potential future loss?

By possible interactions with

- Opening / deepening of the Drake passage
- Reorganization in ocean circulation, e.g. AMOC, Circumpolar current
- Changes in hydrological cycle, weathering, and carbon cycle



Solving the Riddle of the Ice Ages

LETTER

Critical insolation–CO₂ relation for diagnosing past and future glacial inception

A. Ganopolski¹, R. Winkelmann² & H. J. Schellnhuber^{1,3}

The past rapid growth of Northern Hemisphere continental ice sheets, which terminated warm and stable climate periods, is generally attributed to reduced summer insolation in boreal latitudes^{1–3}. Yet such summer insolation is near its minimum at present⁴, and there are no signs of a new ice age⁵. This challenges our understanding of the mechanisms driving glacial cycles and our ability to predict the next glacial inception⁶. Here we propose a critical functional relationship between boreal summer insolation and global carbon dioxide (CO₂) concentration, which explains the beginning of the past eight glacial cycles and might anticipate future periods of glacial inception. Using an ensemble of simulations generated by an Earth system model of intermediate complexity constrained by palaeoclimatic data, we suggest that glacial inception was narrowly missed before the beginning of the Industrial Revolution. The missed inception can be accounted for by the combined effect of relatively high late-Holocene CO₂ concentrations and the low orbital eccentricity of the Earth⁷. Additionally, our analysis suggests that even in the absence of human perturbations no substantial build-up of ice sheets would occur within the next several thousand years and that the current interglacial would probably last for another 50,000 years. However, moderate anthropogenic cumulative CO₂ emissions of 1,000 to 1,500 gigatonnes of carbon will postpone the next glacial inception by at least 100,000 years^{8,9}. Our simulations demonstrate that under natural conditions alone the Earth system would be expected to remain in the present delicately balanced interglacial climate state, steering clear of both large-scale glaciation of the Northern Hemisphere and its complete deglaciation, for an unusually long time.

In accordance with classical Milankovitch theory¹⁰, interglacial–warm intervals with the lowest global ice volume—occur during periods of high summer insolation in the boreal latitudes of the Northern Hemisphere. In the past, a decrease in Northern Hemisphere insolation to below its present-day level always led to the end of interglacials and rapid growth of continental ice sheets¹¹, accompanied by a reduction in CO₂ concentration^{12,13}. However, at present, although summer insolation at 65° N is close to its minimum¹⁴, there is no evidence for the beginning of a new ice age. On the contrary, sea level, which reflects changes in global ice volume, remained essentially constant over the past several millennia¹⁵.

The most straightforward explanation for the lack of glacial inception at present is that the current insolation minimum is not deep enough because of the low orbital eccentricity of the Earth. However, glacial inceptions have occurred in the past under similar orbital configurations. Marine Isotope Stage (MIS) 11 (about 400,000 years before present, 400 kyr BP) is often considered a close paleo-analogue for the current interglacial (the Holocene, or MIS1) owing to the similarly low values of the eccentricity of Earth's orbit and similar CO₂ level at that time¹⁶ (Fig. 1). The only difference between the insolation minimum at about 400 kyr BP and the present one is a lower obliquity during MIS11.

With respect to the orbital parameters, MIS19 (about 800 kyr BP) is an even closer analogue for the Holocene (see Fig. 1). Following this analogy, it has been suggested that the current interglacial will end naturally within the next 1,500 years if the CO₂ concentration stayed at a level of about 280 parts per million (p.p.m.), as was the case at the end of MIS19 (ref. 13). However, during the late-Holocene to the beginning of the industrial era, the CO₂ concentration was at

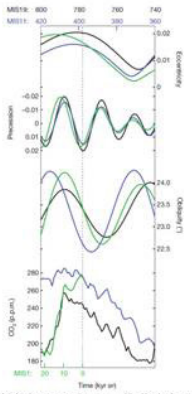


Figure 1 | Orbital parameters. Comparison of Earth's orbital parameters and CO₂ concentrations for MIS19 (green), MIS11 (blue) and MIS1 (black). The vertical dashed line corresponds to the present day for MIS1 and MIS19.

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RESEARCH NEWS & VIEWS

Earth's narrow escape from a big freeze

An equation has been derived that allows the timing of the onset of glaciations to be predicted. This confirms that Earth has just missed entering a new glacial period, and is unlikely to enter one for another 50,000 years. See Letter p.200

WINKELMANN

A subject of much debate is whether atmospheric levels of carbon dioxide (CO₂) were already significantly altered by emissions associated with human activities before the Industrial Revolution in the eighteenth century. One estimate suggests that the atmospheric concentration of CO₂ would have been only 240 parts per million (p.p.m.) in an agriculture-free world, rather than 280 p.p.m., as was assumed just before the Industrial Revolution¹. On page 200 of this issue, Ganopolski et al.² report modelling studies confirming that we would now be entering an ice age if the concentration had remained at 240 p.p.m. In contrast, they report that glacial inception—the onset of an ice age—could not have occurred if CO₂ concentrations that were typical of the eighteenth century.

The Quaternary period has conventionally been divided into two epochs: the Pleistocene, which lasted from about 2.58 million to 12,000 years ago, and the Holocene, which followed the Pleistocene and continues to the present day. The Pleistocene was a time of great, recurring glacial cycles interrupted with interglacial periods, during which environmental conditions were similar to those occurring today. During the Holocene—the latest interglacial period—human invented agriculture, and their impact on the environment increased at an exponential rate. One of the significant effects of this was the rising concentration of CO₂ in the atmosphere. But at what point does this impact become sufficiently large to affect climate and glacial inception?

A modelling study³ in 2009 established that pre-industrial levels of CO₂ were high enough to guarantee a period of interglacial

using simple dynamical systems for climate prediction, calibrated using data about past CO₂ levels and ice volumes. All of these studies used different models and assumptions, but they broadly agree on the potential timing for a glacial inception because their forecasts are determined by predictable drops in incoming solar radiation (insolation) in the Northern Hemisphere caused by changes in Earth's orbit.

Ganopolski and co-workers' study is an advance on previous work because it provides a single equation for predicting when glacial inception will occur. The researchers used that, as the Earth system model they used for their study (CLM3ER-2), to begin to test when insolation in the Northern Hemisphere at the summer solstice falls below a certain value that depends logarithmically on the concentration of atmospheric CO₂. They were thus able to work out an equation that describes this behaviour.

To calibrate the equation, the authors performed several simulations that differed by the value of a parameter that controls cloud height in their model. This sampling process effectively generates a family of model versions, which the authors tested to see which ones predicted past glacial inceptions. Past glaciations and interglacials have been identified on the basis of isotope data from marine sediments, and they follow a numbering scheme in which isotope stages⁴ with odd numbers roughly correspond to interglacials. The authors paid special attention to the glacial inception after marine isotope stages 19 and 21, and to the perturbation after marine isotope stage 1 (that is, the Holocene), because insolation evolved in a similar way at those times but led to different outcomes (stage 1 did not produce a glacial inception). Only the parameter values that yielded correct simulations of all past glacial inceptions were used to establish the equation.

The authors were thus able to confirm that Earth has a narrow escape from glacial inception during the Holocene: the increase in atmospheric CO₂ levels during this period was sufficient to prevent the planet from entering a glacial period. The authors also report that an interglacial climate would have continued for at least 20,000 years, and more plausibly for 50,000 years, if CO₂ concentrations had been sustained at levels typical of the eighteenth century. However, almost 500 gigatonnes of carbon (GtC; 1 GtC is equivalent

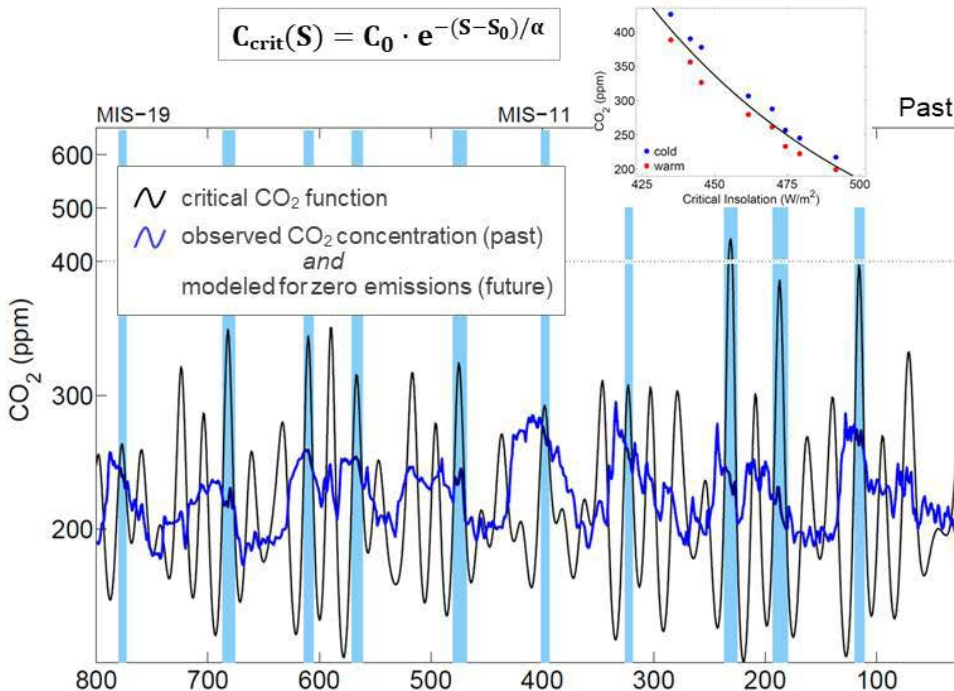


Figure 1 | An eighteenth-century simulation. The atmospheric level of carbon dioxide just before the Industrial Revolution was 280 parts per million, and may already have been affected by emissions associated with human activities. Ganopolski et al. report results suggesting that atmospheric CO₂ levels typical of the eighteenth century were high enough to prevent the onset of a glacial period for 50,000 years.

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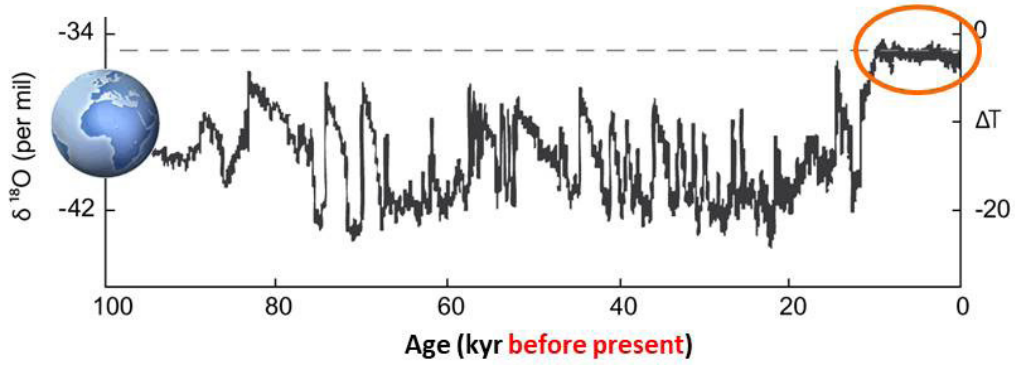
Critical CO₂ Concentration-Insolation Function

$$C_{crit}(S) = C_0 \cdot e^{-(S-S_0)/\alpha}$$



Ganopolski, A., Winkelmann, R., Schellnhuber, H.J. (2016): Critical insolation–CO₂ relation for diagnosing past and future glacial inception. Nature

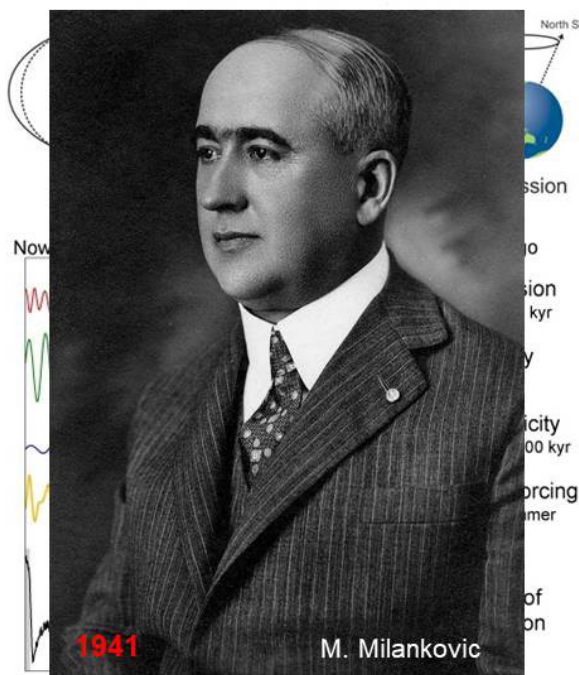
The Holocene: *From Glacial Chaos to Climate Paradise*



Source: Johan Rockström

Why Does the Climate Change at All? Longer-Term Factors:

Milankovic Cycles

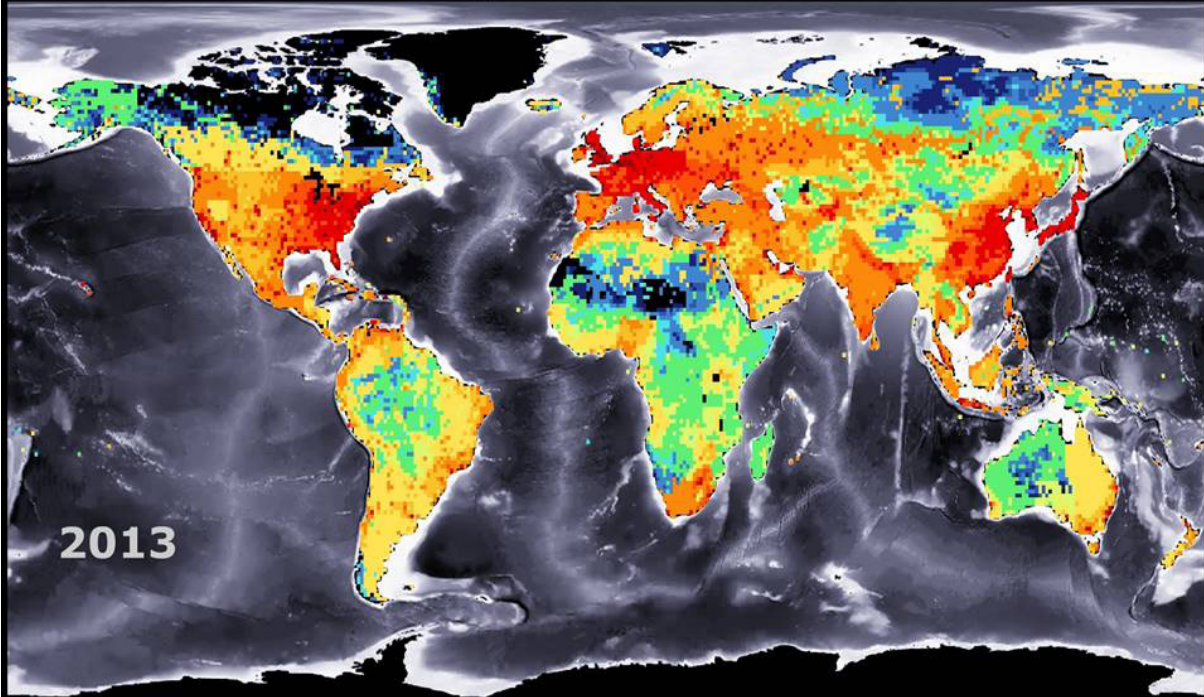


Source: Global Warming Art

The Greenhouse Effect



The C-Story of Human Civilization



2013

Cumulative human carbon dioxide emissions [Mt C]

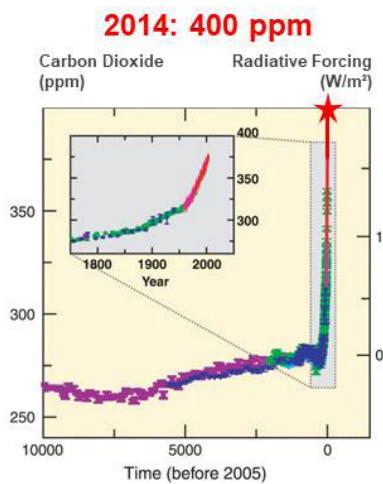


Data Source: CDIAC 2016 (Andres, R.J., T.A. Boden, and G. Marland. 2016)

Bathymetry: NASA, Earth Observatory

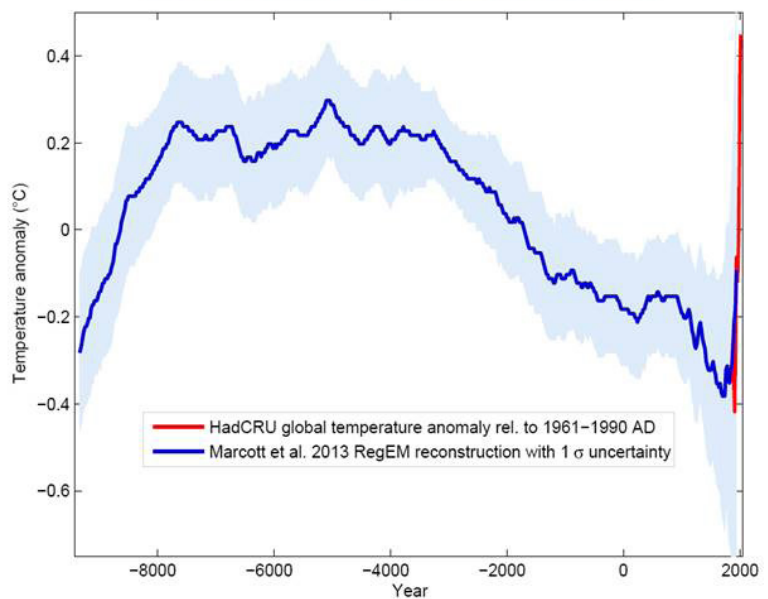
Animation: PIK 2016

Rising CO₂ Concentration



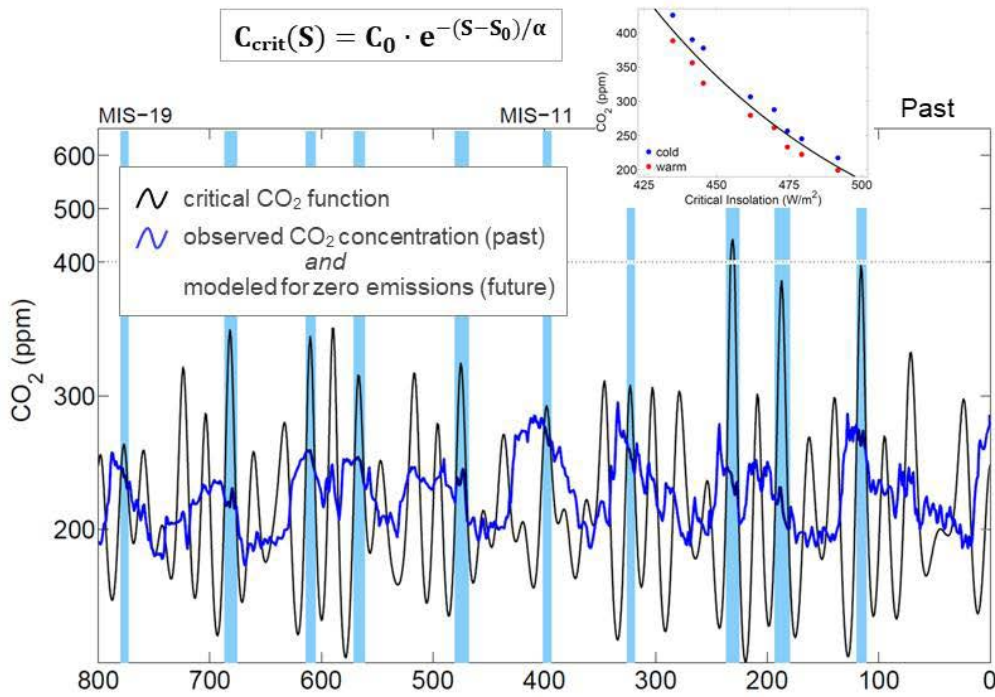
IPCC 2007

Global Reconstruction of Holocene Temperature



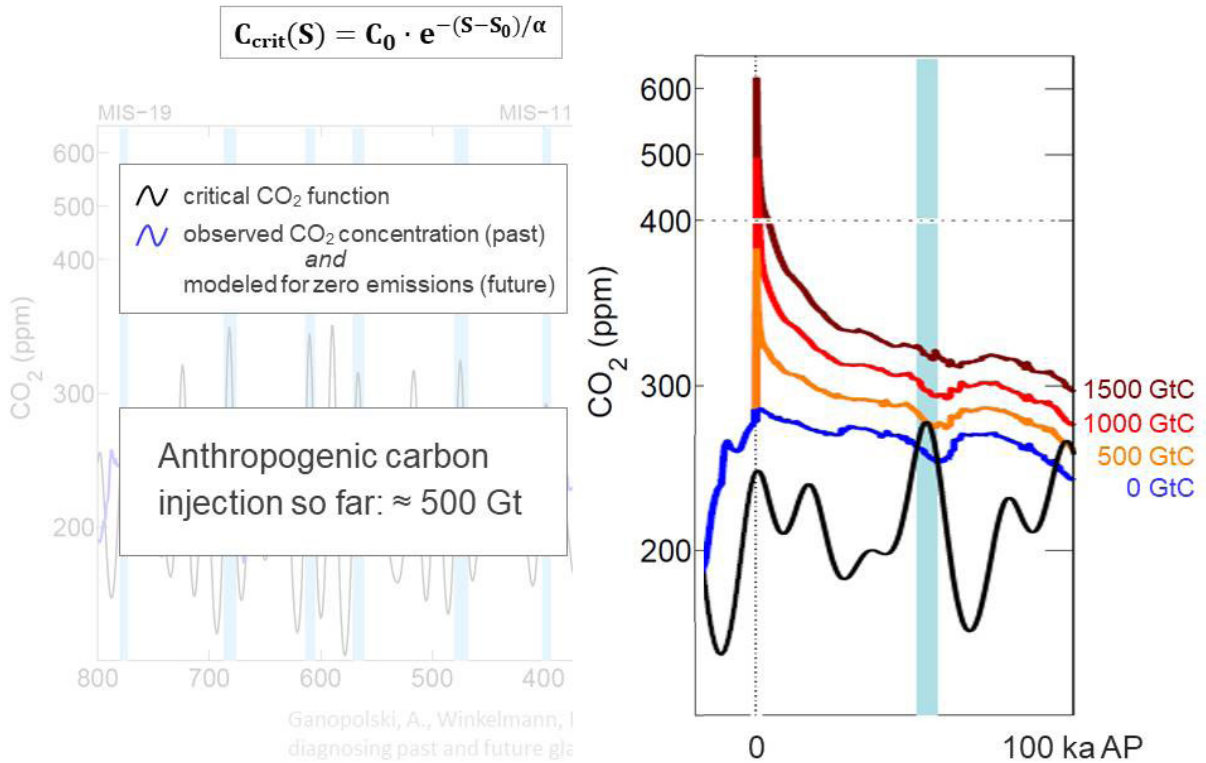
Marcott *et al.* 2013, Science

Critical CO₂ Concentration-Insolation Function



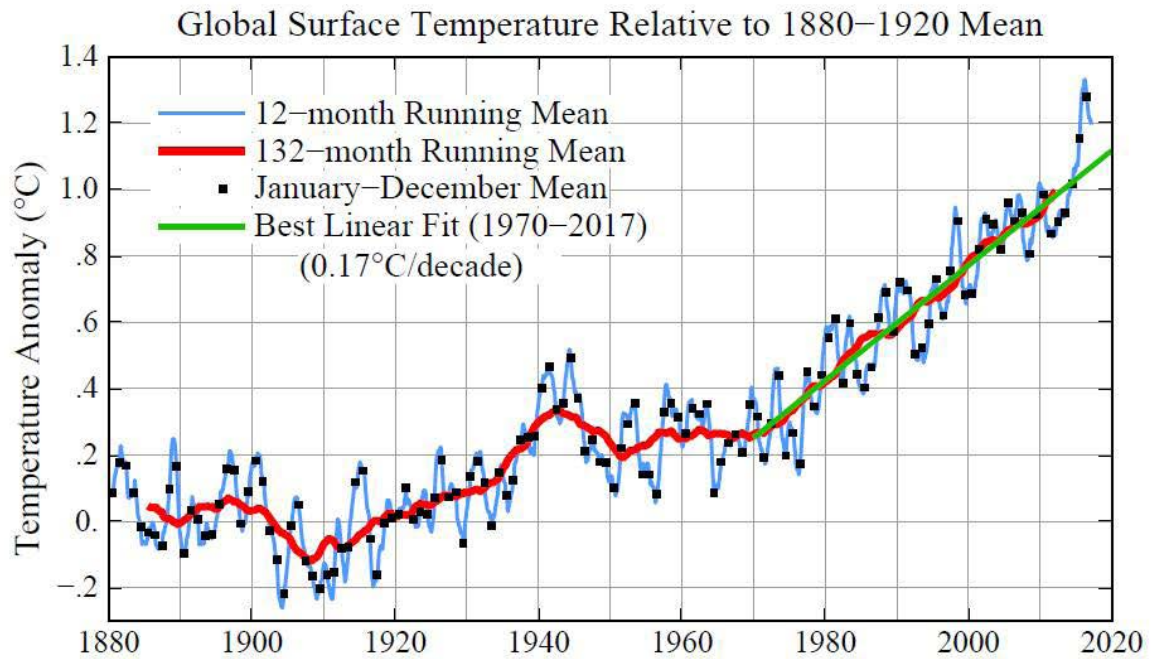
Ganopolski, A., Winkelmann, R., Schellnhuber, H.J. (2016): Critical insolation-CO₂ relation for diagnosing past and future glacial inception. Nature

Critical CO₂ Concentration-Insolation Function



Ganopolski, A., Winkelmann, R., Schellnhuber, H.J. (2016): Critical insolation-CO₂ relation for diagnosing past and future glacial inception. Nature

Current Development of Global Warming



The Paris Agreement

Nations Unies

Conférence sur les Changements Climatiques 2015

COP21/CMP11

Paris, France



B11-dquelle: <https://www.wmo.int/media/>

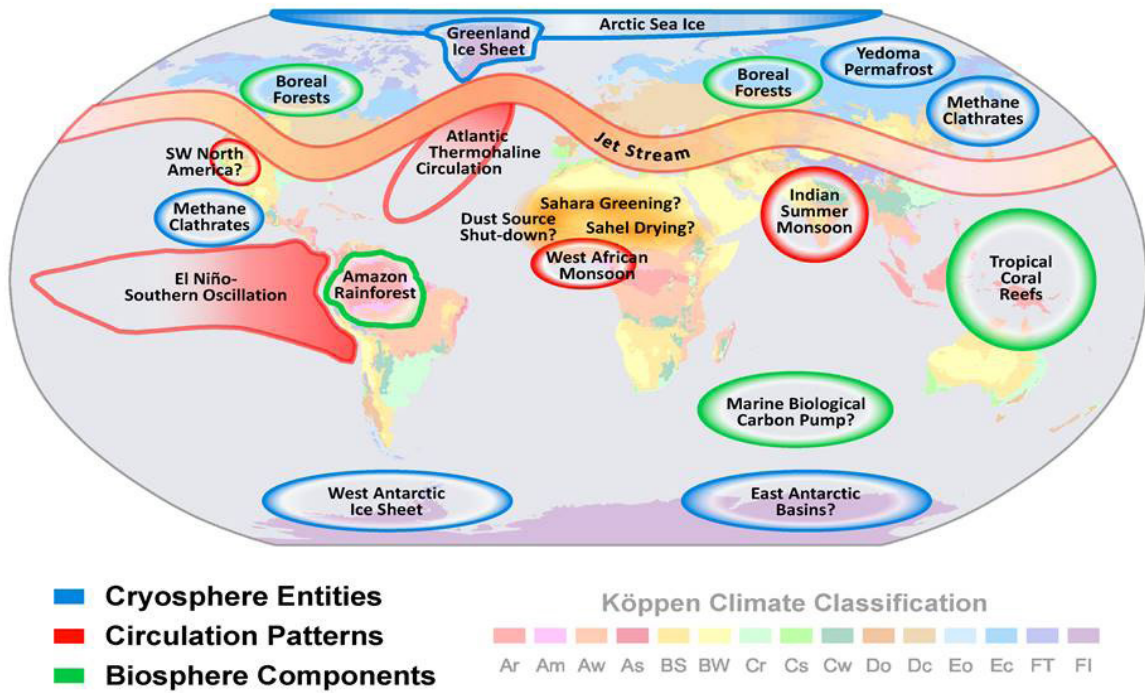
Limiting global warming “well below”
2 degrees Celsius

Net-zero emissions of greenhouse gases by mid-21st century

National emission targets regularly reviewed and tightened

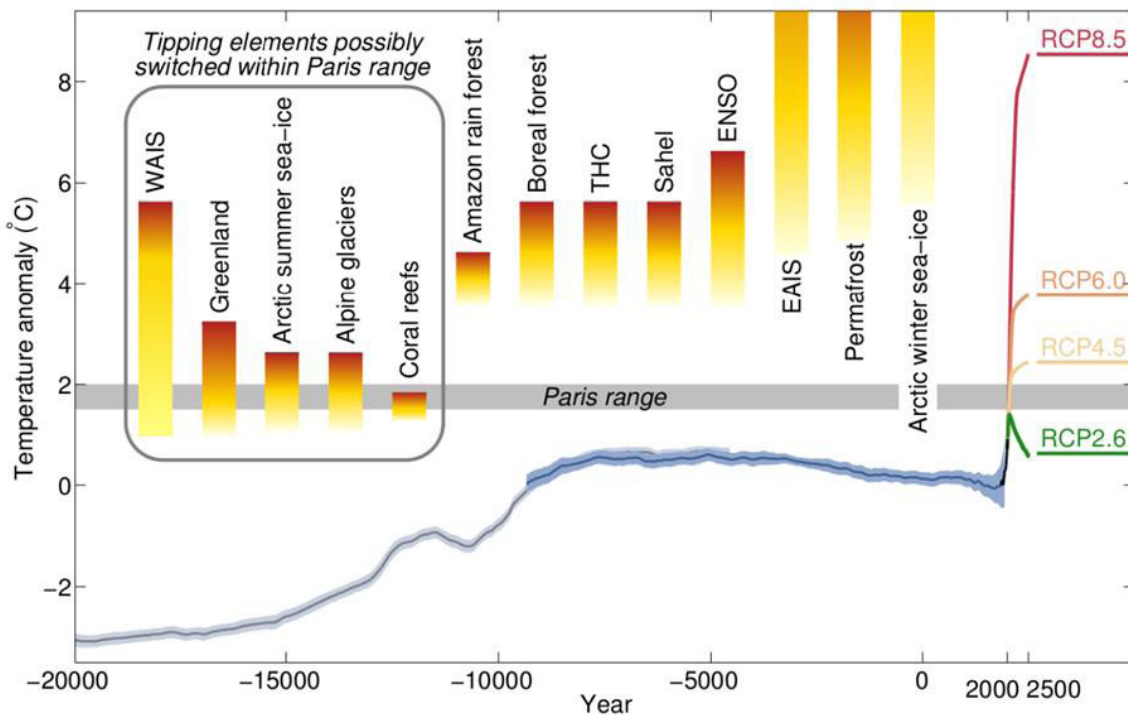
Developed countries provide 100 billion USD per year between 2020-2025

Looming Risks: Tipping Elements in the Earth System



PIK2017

Tipping Points Related to 2°C-Guardrail



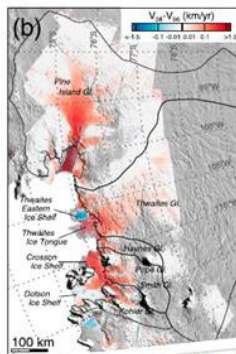
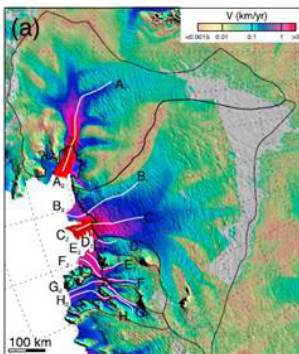
Schellnhuber et al., Nature Climate Change, 2016

The Die is Cast!



ca. 1.2 and 3.3 m Sea-Level Equivalent, resp.

Ice-Flow Speed →



← Acceleration of Ice Flow

nature climate change

PUBLISHED ONLINE: 12 JANUARY 2014 | DOI: 10.1038/NCLIMATE2098

LETTERS

Retreat of Pine Island Glacier controlled by marine ice-sheet instability

L. Favier^{1,2}, G. Durand^{1,2*}, S. L. Cornford³, G. H. Gudmundsson^{4,5}, O. Gagliardini^{1,2,6}, F. Gillet-Chaulet^{1,2}, T. Zwinger⁷, A. J. Payne³ and A. M. Le Brocq⁸

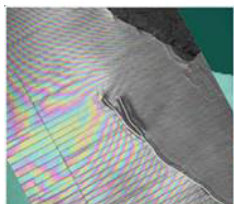
Geophysical Research Letters
Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011

E. Rignot^{1,2}, J. Mouginot¹, M. Morlighem¹, H. Seroussi², and B. Scheuchl¹
 Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013
 J. Mouginot¹, E. Rignot^{1,2}, and B. Scheuchl¹

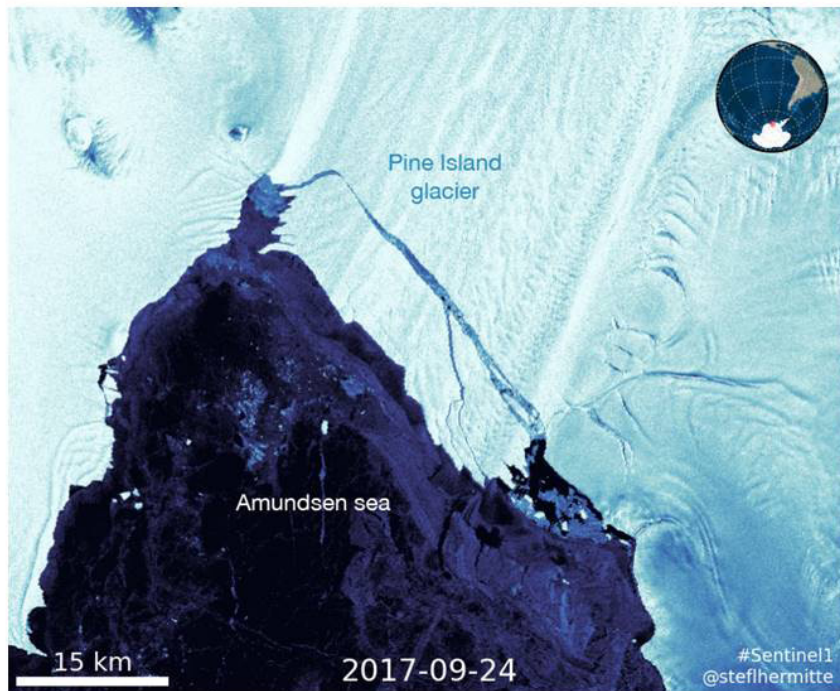


Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica
 Ian Joughin *et al.*
Science **344**, 735 (2014);
 DOI: 10.1126/science.1249055

Crack in Antarctica's Larsen C Ice Shelf



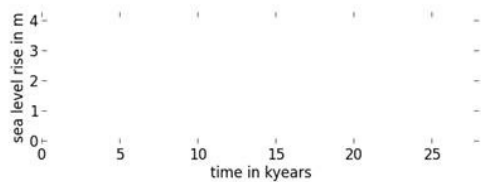
A Key Antarctic Glacier Just Lost a Huge Piece of Ice



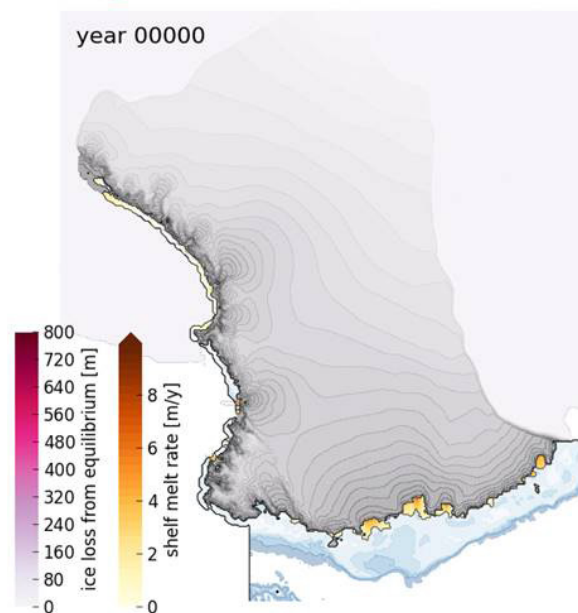
Pictures: Washington Post

Sea-level Rise After Ice Plug Removal

critical threshold
< 80 mm sea-level equiv.

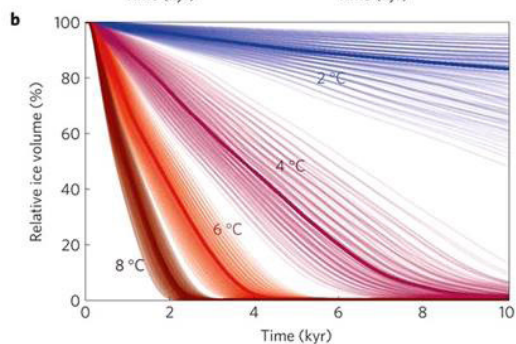
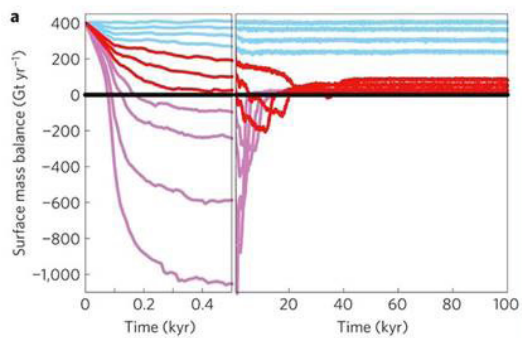


self-sustained long-term
sea-level rise of 3 - 4 m

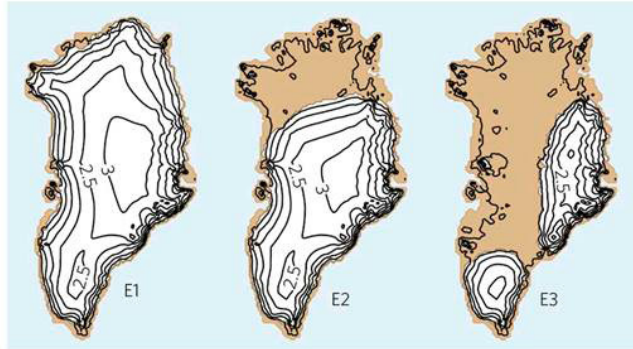


Mengel & Levermann, *Nature Climate Change*, 2014.

Irreversible Loss of Greenland Ice-Sheet Could Start with 1.6°C Temperature Rise Relative to Preindustrial



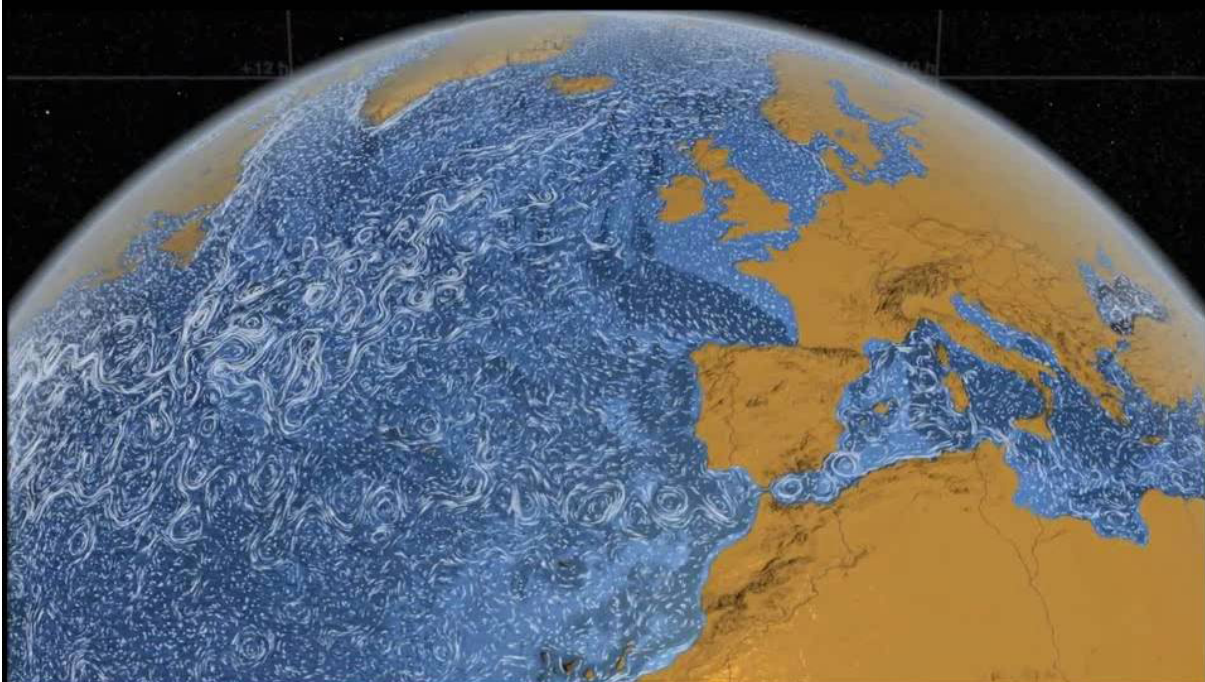
Transient GIS evolution



Equilibrium states of the GIS

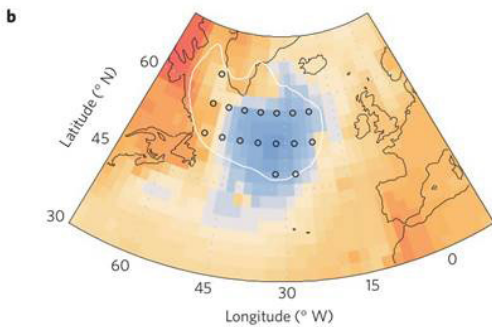
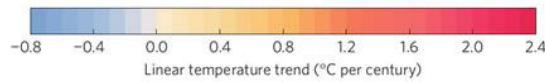
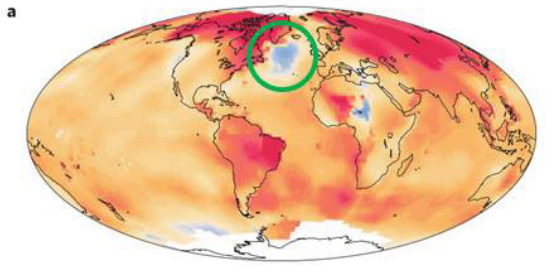
Robinson et al. 2012, Nature Climate Change

Tracing the Flow of Surface Currents



NASA'S GODDARD SPACE FLIGHT CENTER

Exceptional Slowdown and Shrinking Stability of the Atlantic Ocean Overturning Circulation



Rahmstorf et al., 2015

SCIENCE ADVANCES | RESEARCH ARTICLE

CLIMATOLOGY

Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate

Wei Liu,^{1*} Shang-Ping Xie,² Zhengyu Liu,³ Jiang Zhu²

Changes in the Atlantic Meridional Overturning Circulation (AMOC) are moderate in most climate model projections under increasing greenhouse gas forcing. This intermodel consensus may be an artifact of common model biases that favor a stable AMOC. Observationally based freshwater budget analyses suggest that the AMOC is in an unstable regime susceptible for large changes in response to perturbations. By correcting the model biases, we show that the AMOC collapses 300 years after the atmospheric CO₂ concentration is abruptly doubled from the 1990 level. Compared to an uncorrected model, the AMOC collapse brings about large, markedly different climate responses: a prominent cooling over the northern North Atlantic and neighboring areas, sea ice increases over the Greenland-Iceland-Norwegian seas and to the south of Greenland, and a significant southward rain belt migration over the tropical Atlantic. Our results highlight the need to develop dynamical metrics to constrain models and the importance of reducing model biases in long-term climate projection.

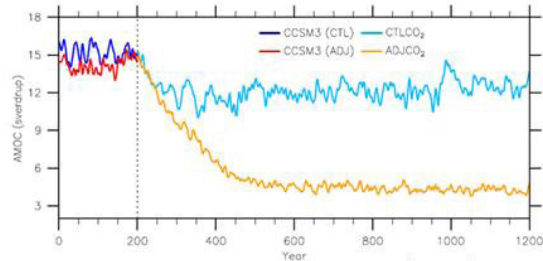
INTRODUCTION

Current climate models suffer from biases (1), and therefore, it is critically important to assess the potential impact of the model biases on future climate projections. One vital player for climate change is the Atlantic Meridional Overturning Circulation (AMOC). With a warm, northward near-surface flow and a colder, southward return flow at depth (2), the AMOC carries oceanic heat northward and contributes moderate climate to the U.K. and northwest Europe (3). There is evidence that the AMOC has slowed down since the early 20th century, although this long-term declining trend of AMOC strength is subject to great uncertainty (3). Under future global warming, the AMOC is predicted to further weaken (1, 4–6), but the degree of the change is uncertain. Most climate models predict a moderate slowdown but not a complete shutdown of the AMOC (5). These different AMOC responses essentially depend on the circulation stability (1–3). Recent studies (7–10) point to a serious bias in AMOC stability in current climate models. Observational analyses (9–10) suggest an unstable modern AMOC (with multiple equilibria), meaning that the AMOC may switch between “on” and “off” modes in the future, as it did

between the Atlantic and the Arctic (M_{OC}). For example, Wooster et al. (7) show that low models in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (20) exhibit a rapid collapse of future AMOC, although AG₂ classifies 40% of them as being in an unstable regime. By contrast, AMOC₂ accurately denotes the freshwater transport induced by the AMOC and therefore can better represent a basin-wide salt advection feedback and the AMOC stability (26). In particular, a divergence of the AMOC-induced freshwater transport (AMOC₂ < 0) indicates an unstable AMOC in response to buoyancy perturbation owing to a positive feedback with salinity advection. We suppose that an energetic modern AMOC induces a freshwater divergence. Under global warming conditions, an initial buoyancy perturbation in the North Atlantic weakens the AMOC and hence the associated freshwater divergence. The reduced freshwater divergence may then lead to an accumulation of freshwater in the North Atlantic, further amplifying the initial freshwater perturbation and resulting in a collapse of the AMOC.

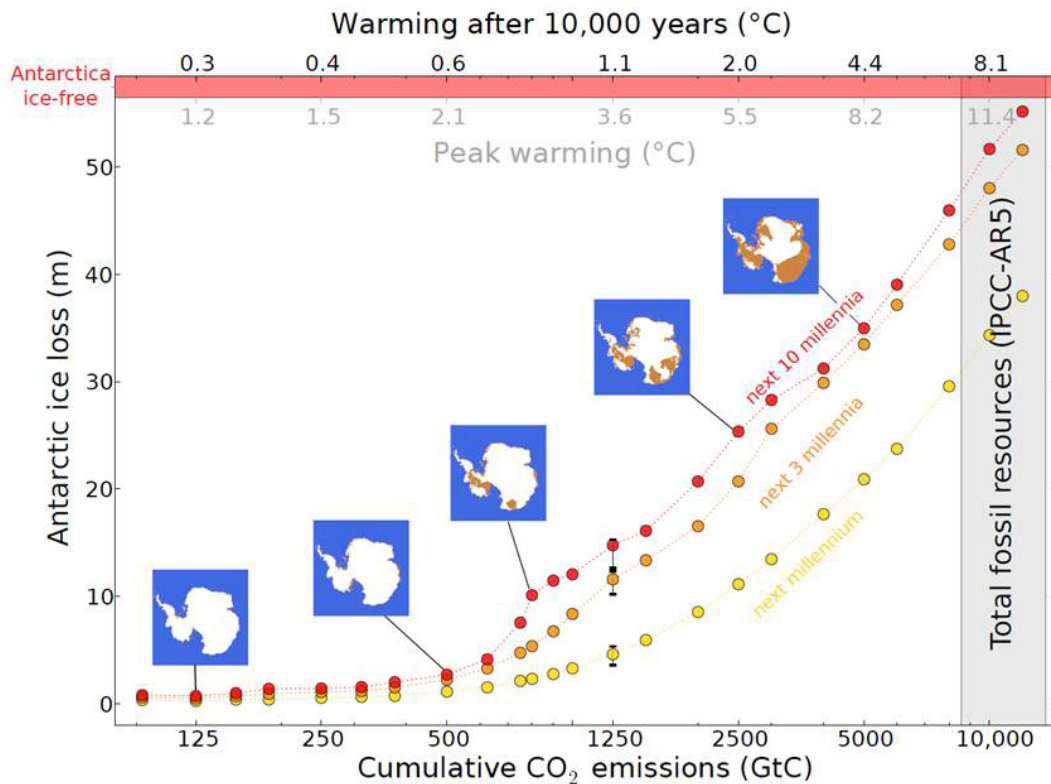
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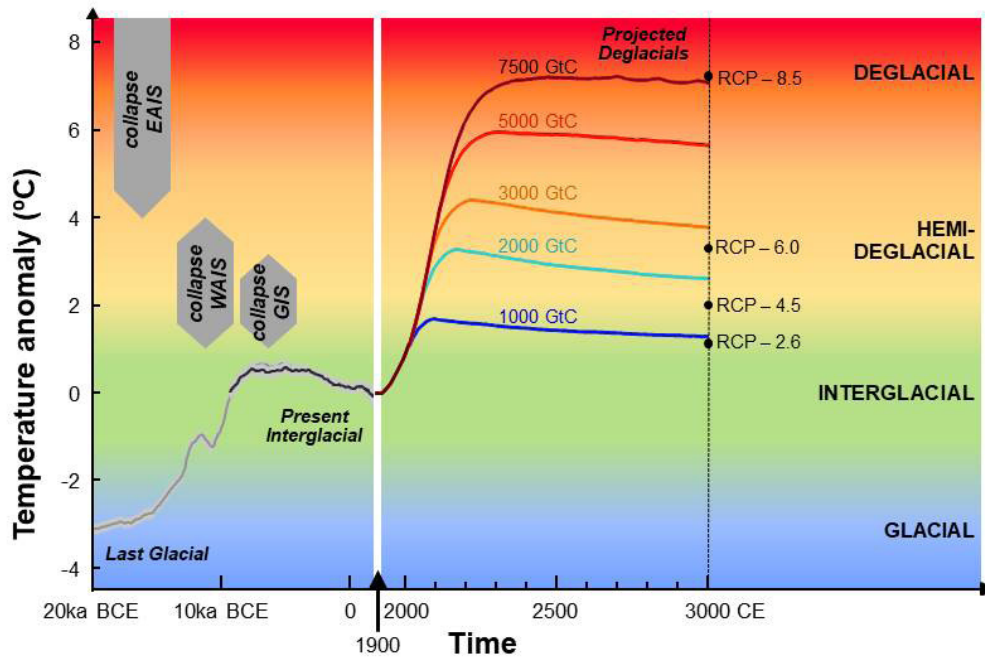
Liu et al., 2017

Sea Level Commitment from Antarctic Ice Loss



Winkelmann et al., Sci. Ad. 2015

Anthropogenic Rush through Cryo-Phase Space

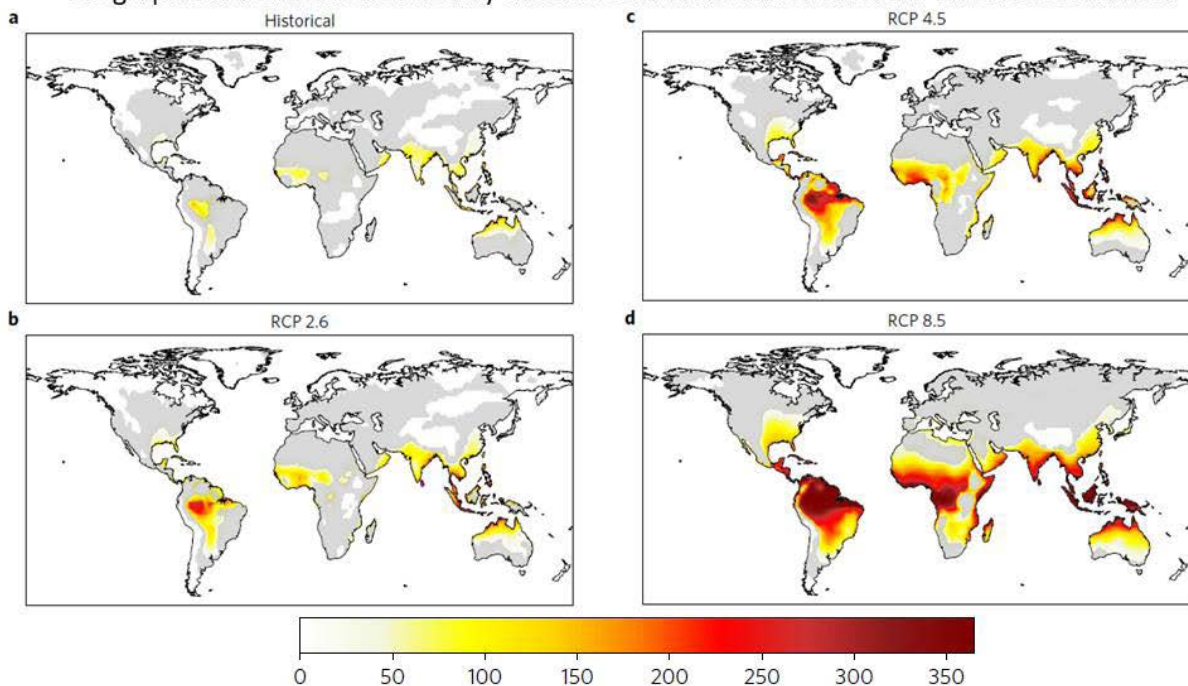


Temperature Reconstructions before 1900 based on Shakun et al. (2012), Marcott et al. (2013)

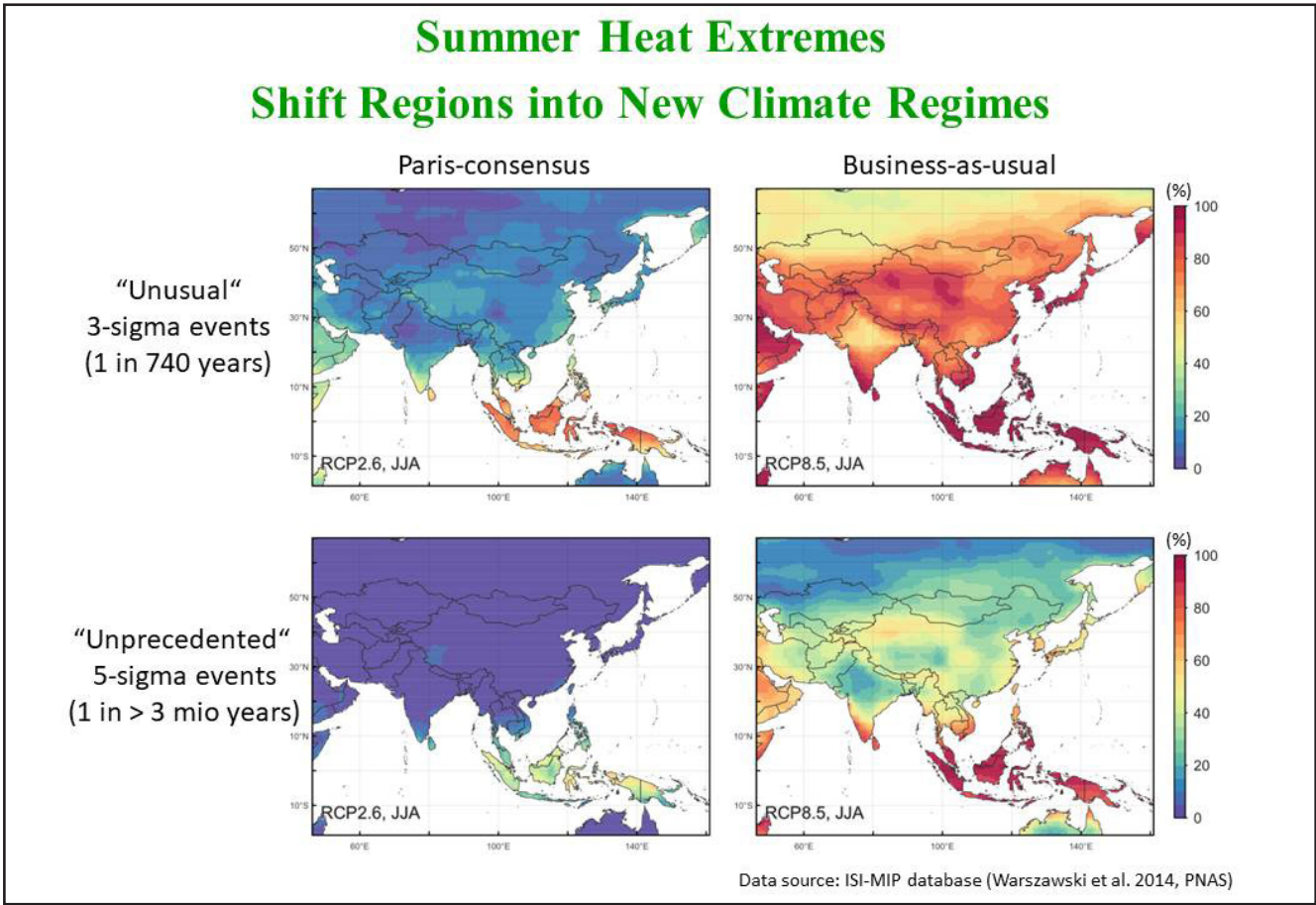
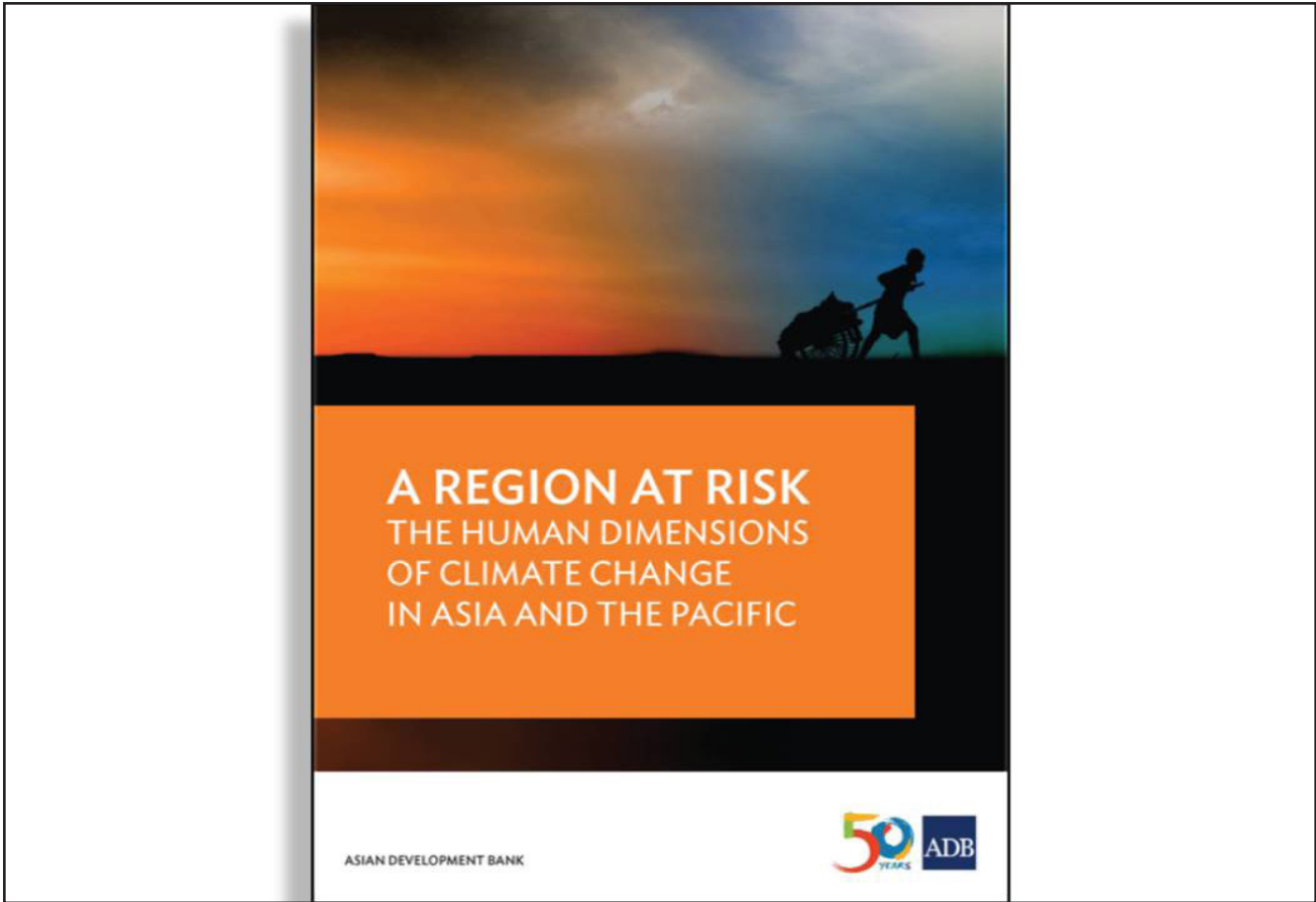
After Ganopolski et al., under review

Climate Change Can Bring about Conditions Exceeding Human Thermoregulatory Capacity

Geographical distribution of deadly climatic conditions under different emission scenarios.



Mora et al., 2017, Nature Climate Change





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Meeting of the Pontifical Academy of Sciences at the Vatican, November 2016



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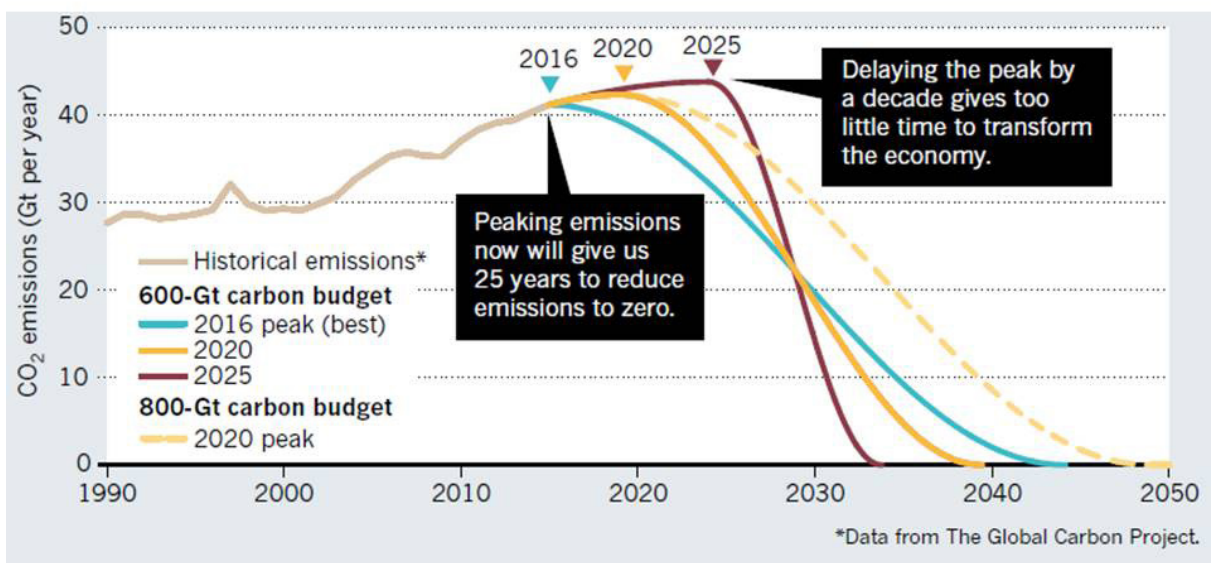
Decarbonizing the world economy will require renewable energy generation from vast solar farms, such as this one in Nevada.

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Figueres, Schellnhuber et al. 2017, Nature

The Carbon Crunch



Figueres, Schellnhuber et al. 2017, Nature

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Image taken by NASA space probe "Lunar Reconnaissance Orbiter" on 12 October 2015