# K42: Future Climate - The 21st Century and Beyond

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***“You cannot confront a power until you know what it is. Our first task in this struggle is to understand what we face. Only then can we work out what to do”***

*-Award winning journalist George Monbiot, on climate change*

# *"WE COULD HAVE SAVED IT, BUT WE WERE TOO DAMN CHEAP"*

*- Author Kurt Vonnegut, at Stanford University's Graduation, repeating quote from Bergeron, **"…to be etched in the walls of the Grand Canyon for the flying saucer people to find"***

# The Future…

- 1. We'd like to believe the IPCC, but can't
- 2. Equilibrium Climate Sensitivity (**ECS**) to CO2
- 3. The irreversibility of climate change
- 4. Dropping oxygen levels in atmosphere and ocean
- 5. Sea Level Rise. New predictions
- 6. Ice sheet grounding and instability
- 7. Ocean acidification
- 8. Weather changes – rising intensities
- 9. AMOC shutdown and Super Storms
- 10. PCF: Permafrost Carbon Feedback and methane
- 11. Crop yields in a warming world
- 12. CO2 effects on insects and food chain
- 13. Regional Forecasts, including California
- 14. Societal instability, and other effects
- 15. Collapse of Biodiversity
- 16. Runaway Greenhouse Syndrome? (**a long way off**)
- 17. Near Term Human Extinction!? **(No. Relax! A bit, anyway)**

# 1. The Setting - The Flawed IPCC Process:

## Insures Scenario Assumptions are Unreasonably Optimistic

## The latest AR5 Report assumes, even with no policy changes, even stronger spontaneous decarbonization and efficiency gains than the AR4 did, with no justification.

- *"A comparison of the carbon (CI) and energy intensity (EI) reductions in the RCP baseline scenarios for 2005-2020 and 2020-2100 shows that assumptions of spontaneous decarbonization rates in the reference scenarios are similar to the results from the SRES (in AR4). In fact, for the RCPs (2.6 and 8.5) where the reference scenarios are derived from SRES families, CI and EI reductions are even larger over the 2020-2100 period.* ***This implies that the IPCC continues to use very aggressive assumptions of spontaneous technological advancement and deployment as the basis for evaluating mitigation efforts"*** *(Stevenson and Pielke 2015)*

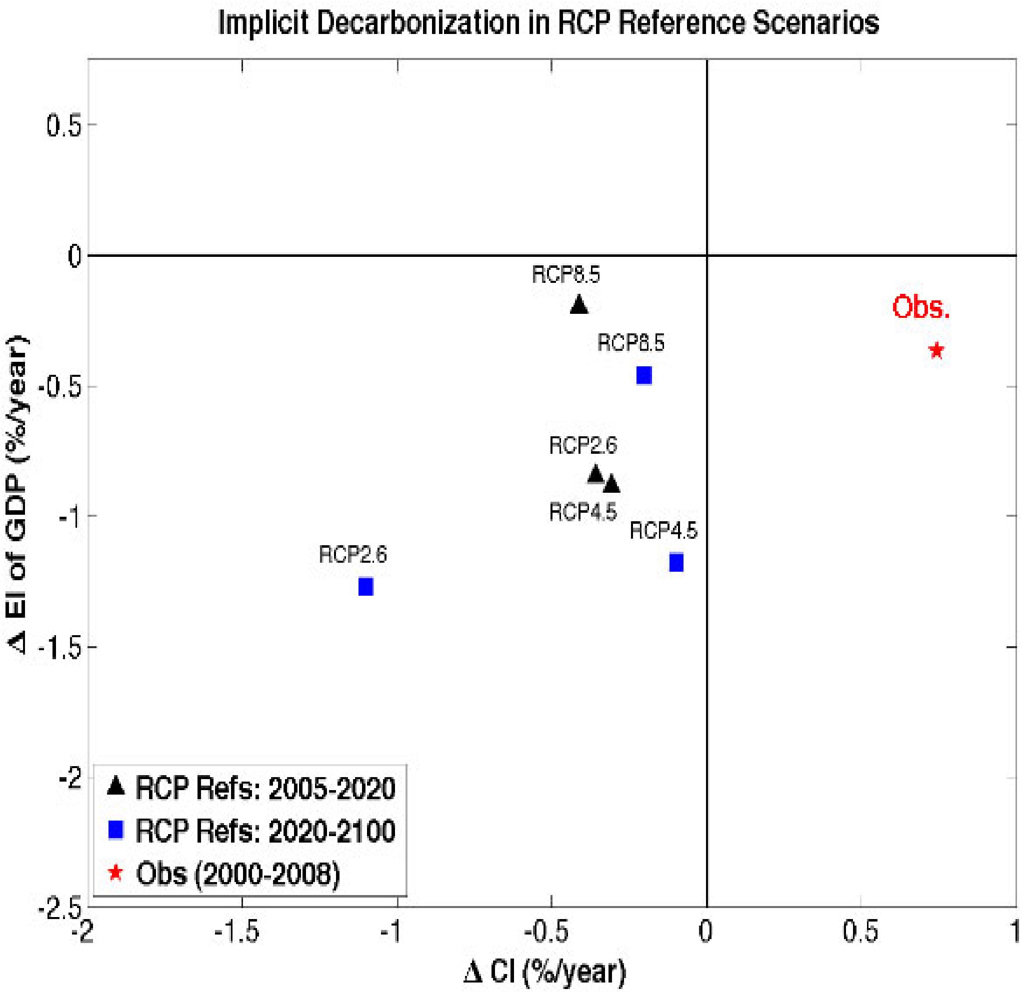
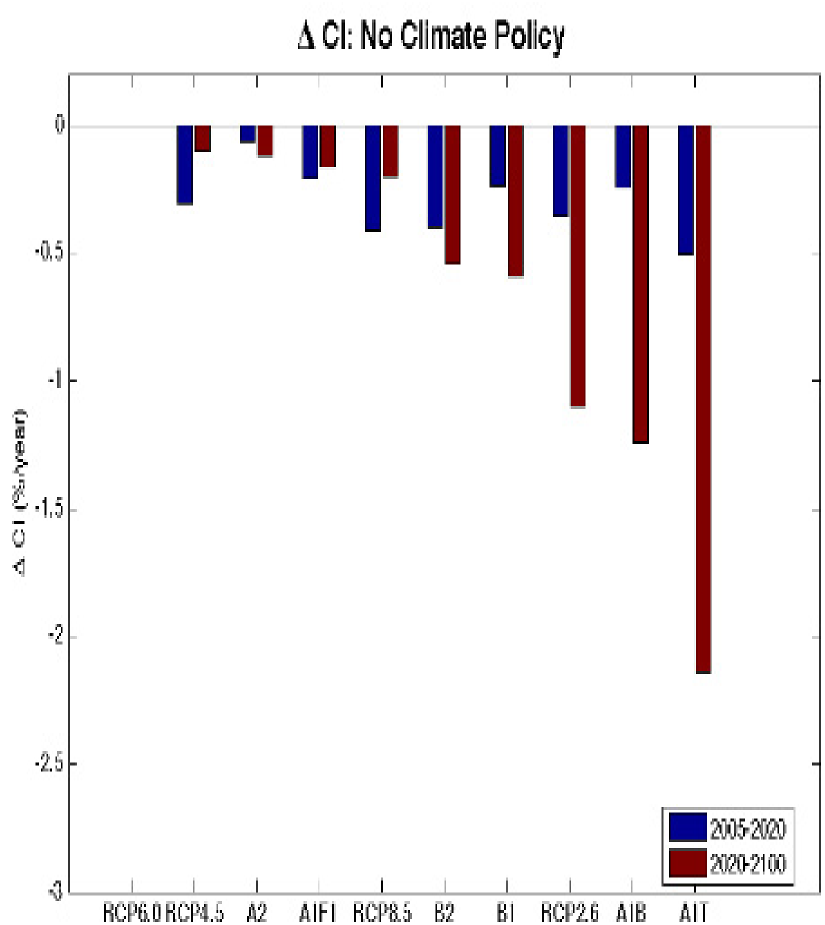
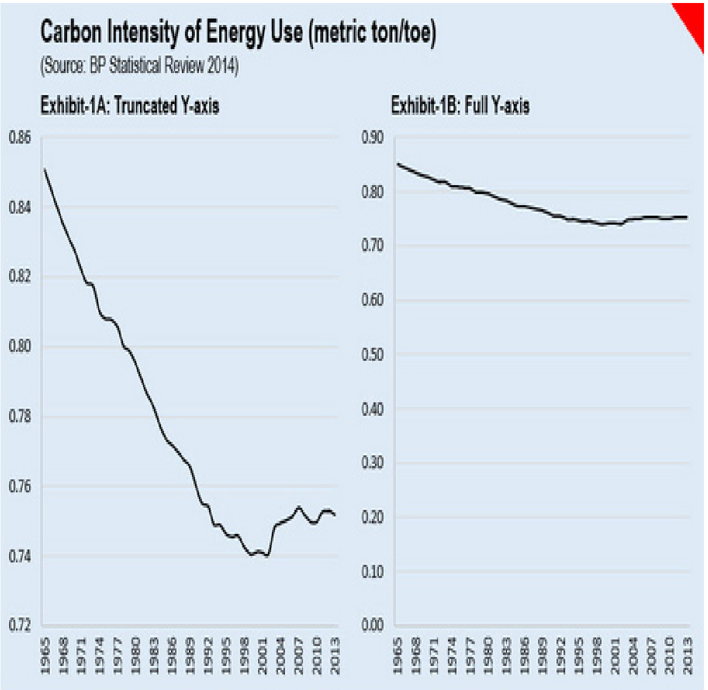



*Figure 1:* Rates of decarbonization in three of the RCP baseline scenarios for which data is available as compared with the observed rate. This figure is modeled after Figure 2 from [1]. Observations are from the World Bank database for 2000-2008.

**IPCC AR5 "Representative Concentration Pathways (RCP scenarios) all assume steep decarbonization (negative CI="carbon intensity of energy", even in the IPCC's simple trend-following RCP 8.5 scenario. All are in significant conflict with actual observations; which is RISING carbon intensity (red star)**

# IPCC Scenarios (left) assume spontaneous strong decarbonizations of ~1-2%/year even with no climate policy action. Compare with actual (right), which shows global decarbonization halted in 2000 and actually gone backwards




## A Closer Look

*From here on, the numbers will show CO2 intensity instead of carbon intensity, because the original data from BP and the EIA report CO2 emissions. To convert CO2 to units of carbon (C), simply divide by 3.667. Carbon intensity and CO2 intensity are used interchangeably in the text – both are ratios that depict emissions generated versus energy produced. In the relevant literature, CO2 intensity is also reported as a ratio of CO2 emissions to GDP--which includes the effects of prices. In this note however, CO2 intensity is measured in physical units--metric tons of CO2 per tonne of oil equivalent (toe). Also, 1965 is the first year for the data published by BP.*

# This recalls the warnings of Tyndall Climate Centre Deputy Director Prof. Kevin Anderson

- Policy people answer to the political system, which has a vested interest in preserving the political/economic paradigm of growth and competitiveness. They are deemed successful in their work to the extent they paint rosy pictures within the existing political/economic paradigm.
- Also, the IPCC's policy statements must endure the softening re-wordings from officials of the worst carbon polluters on Earth before publication. **The IPCC process is badly tainted**
- These conflicted motivations lead to the tendency towards rosy assumptions even **before any climate policy enactments,** which therefore minimize the severe dangers which are, in fact, indicated by the evidence.

# On Coming Climate Change…

*"…Scientists were not telling the whole truth. Because they were discouraged from telling the whole story, even explicitly told not to do so."*

**Page 4 of [James Hansen, 2019]**

# I have respect for the IPCC scientists work in quality journals

- I have little respect, however, for the U.N. overlords who censor and manipulate the official document releases from the scientists.
- By choosing members with a *“range of views”* and then insisting on 100% agreement to all publications, they insure veto-power to the small minority of industry-sponsored “scientists”, and the IPCC political representatives, thus biasing towards bland and unthreatening pronouncements.

# The IPCC: Sold to Scientists as a Means for Scientists to Influence Policy…

- …but in operation (and design?), by encapsulating the scientists within the UN mandated rules for "consensus" with policy overlords (the UN is dominated by the most powerful carbon emitters and pro-economic growth countries on Earth), the IPCC acts as a mechanism to instead **muzzle** and **neuter** the science.

# The Political Manipulation of the IPCC

- More and more scientists are complaining that the latest AR, as well as earlier ones, have a “vast blind spot” on the role of the fossil fuel and right-wing sponsored mis-information campaigns.
- *“This is an important barrier to climate action, but it is never addressed,” said Professor Robert Brulle of Drexel University, who* ***has published research on the funding and influence of climate science denial efforts.***
- *“A large existing literature on this was ignored by the IPCC,” he added.*

# Even for Good Academic Scientists - Funding Support is by Pro-Growth Policy Govts…

***"The modelling community is actually self-censoring its research to conform to the dominant political and economic paradigm..."***

***-- Tyndall Climate Centre Deputy Director, Dr. Kevin Anderson***

***"We've reached a point where we have a crisis, an emergency. But people don't know that. There's a big gap between what's understood about global warming by the scientific community, and what is known by the public and policymakers"***

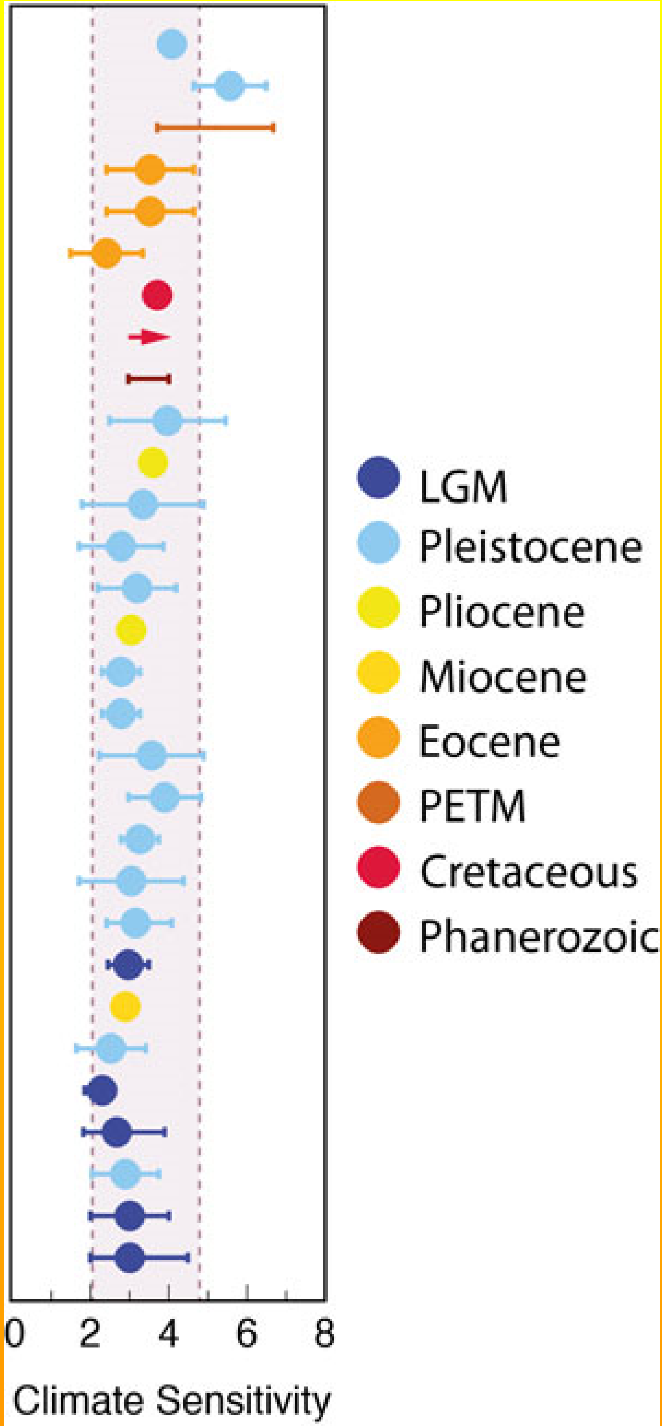
-Prof. James Hansen, 2008

- ***"As a public health professional (and as a human), I find the prospect of 3 or 4 degree C of global warming to be nothing short of <u>terrifying</u>. We need to do a much better job of sharing what we know about the likely impacts of global warming, <u>because people are not nearly as worried as the situation warrants."</u>***

**-Ed Maibach, director of the George Mason University Center for Climate Change Communication**

# 2. Equilibrium Climate Sensitivity:

# Climate Temperature Sensitivity to a Doubling of Atmospheric $CO_2$




# ECS = Equilibrium Climate Sensitivity

- **ECS == Final global avg temperature change after doubling CO2 from 280 to 560 ppm, after all "fast" feedbacks have stabilized**
- Results at left from the PALEOSENS collaboration.
- Uses Paleo climate data from warmer and higher CO2 epochs of the past 100 million years
- **ECS= +2.5C to +4.5C temperature rise, when ECS is averaged over the climate states studied (i.e. <u>ignoring whether ECS may depend on climate state</u>)**

# Amplifying Feedbacks Underestimated

- How much will global average temperatures rise, given a doubling of $CO_2$ from the 280ppm of the pre-industrial period to 560ppm?
- **Transient Climate Sensitivity (TCS)** = what is the temperature rise at the moment $CO_2$ hits 560ppm? Not a well-definable nor useful number, but often you'll see climate denial people try to use it because it will be LOWER than…
- **Equilibrium Climate Sensitivity (ECS)** = the temperature rise after $CO_2$ hits and remains at 560ppm for as long as it takes for the temperature rise rate to shallow (but true equilibrium takes millennia, as slow feedbacks continue).
- **Earth System Sensitivity (ESS)** relaxes the strict Charney ECS definition (no ice sheet changes, for example) to better reflect actual change given the unprecedented order of magnitude higher forcing we are applying today vs. past

- **Pagani *et al.* (2006)** argue that to explain the **Paleocene-Eocene Thermal Maximum** (PETM) seems to require a much higher sensitivity of global temperatures to a CO2 doubling than had been previously assumed.
- Later studies confirm this.

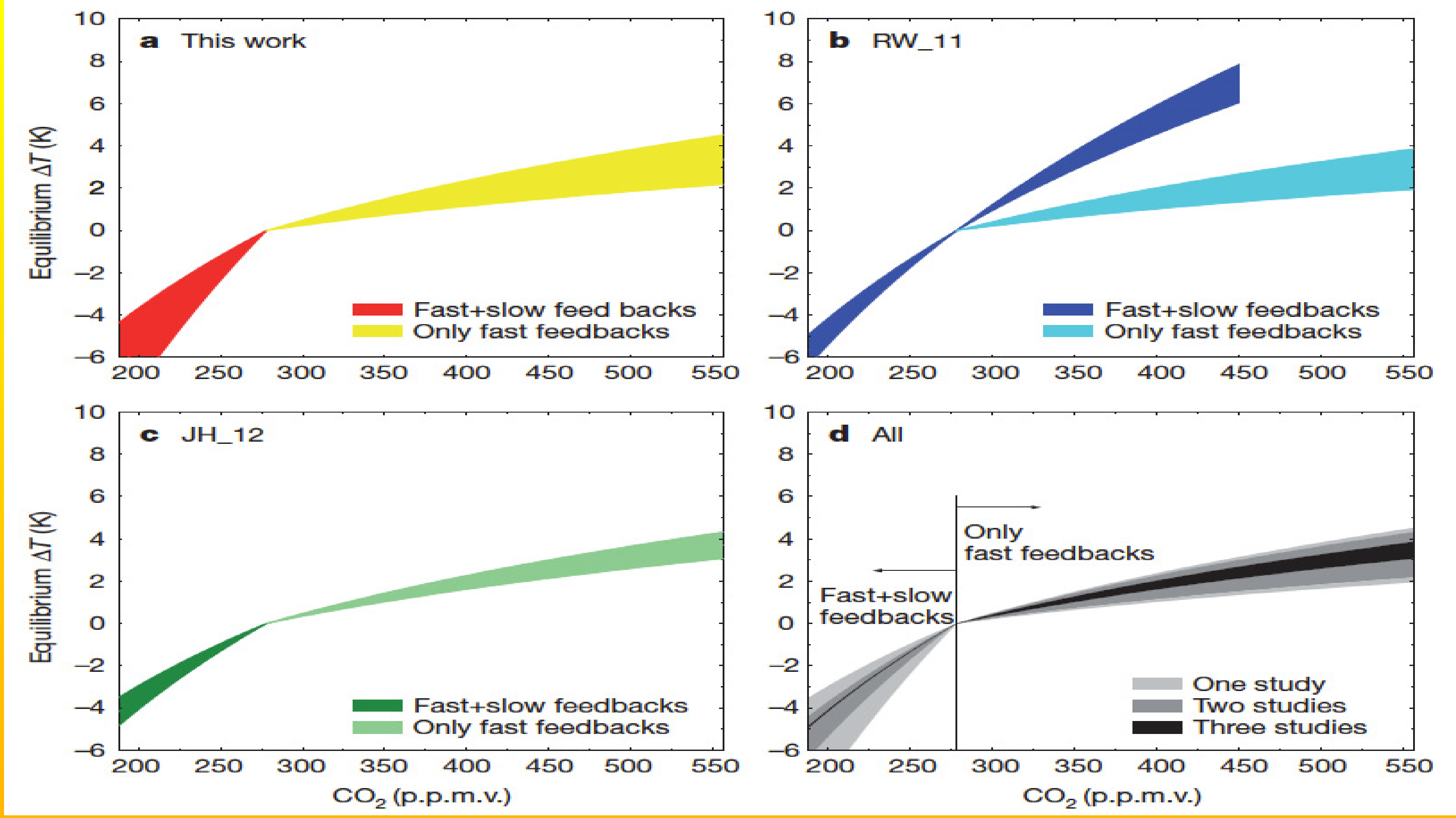
# This implies that amplifying feedbacks (e.g. methane release, loss of low clouds) are more powerful than the standard models assumed.

- This conclusion is supported with the work of **Fasullo *et al.* (2012)**, who finds that **it is the most "alarming" climate models which do the best job of predicting what we have already seen**.
- See an **interview with Fasullo on this work here**.
- **Brient *et al.* 2016 agree**, finding ECS=4.0C and weakening low clouds (which cool climate) with higher temperatures

# Quote From of Fasulo & Trenberth (2012) (Digest here)

- *“In short, while FS12 does not provide a specific measurement of climate sensitivity, it does suggest that the climate models with lower sensitivity ( 'low' here refers to approximately 2 to 3°C surface warming in response to doubled CO2, not the ridiculously low estimates of 1°C or less proposed by contrarians like Richard Lindzen) are not accurately representing changes in cloud cover, and are therefore biased.* ***Climate models with higher sensitivity - in the 3 to 4.4°C ECS range for doubled CO2*** *- more accurately simulate the observational RH (relative humidity) data and thus the response of subtropical clouds to climate change.” (Fasulo & Trenberth 2012)”*
- *(continued on next page)*

- *“If climate sensitivity is on the higher end of the likely range, it does not bode well for the future of the climate. As Fasullo told The Guardian, "our findings indicate that warming is likely to be on the high side of current projections."*
- *In terms of warming over the 21st Century, we are currently on track with IPCC emissions scenario A2, which corresponds to about 4°C warming above pre-industrial levels by 2100 but only if ECS is as low as 3°C for doubled CO2.*
- *Note, that's the warming models expected by the year 2100, but at that point there will still be a global energy imbalance, and thus additional warming will remain 'in the pipeline' until and unless the planet reaches a new equilibrium. An even higher ECS would correspond to even more warming, but anything greater than +2°C will almost certainly be catastrophic.”*
- Even the +3-4C value for ECS looks now to be too low. Worse when you consider longer term (“slow”) amplifying feedbacks. When these are included, **ESS rises to +6C to +7C. In other words, 560ppm CO2 leads to, after thousands of years time scales, to over +6C temperature rise global average (next slide).**




- Equilibrium response of the global temperature as a function of CO2 concentrations, based on three different approaches. a) from the PALEOSENS workshop, using data from the late Pleistocene of the past 800,000yr; b) Using data of the past 20 million yrs from RW_11; c) Based on JH12 using similar data of the past 800 kyr as in a); and d) Combination of all three approaches. Plotted areas include uncertainty estimates of one standard deviation from PALEOSENS . Only RW_11 considers both fast + slow feedbacks for our relevant high CO2 levels (top right)
- ECS with "fast" responses only, is 2.2-4.8 C. Millennium and longer time scale feedbacks raise this to ~+6 C. This confirms earlier work of Hansen *et al.* 2008 who find fast+slow climate sensitivity is +6 C

**Hansen and Sato 2012 find that an <u>average</u> ECS=3.0C (black) fits Earth climate (red) going into and out of Ice Ages for the past ~million years, *i.e.* for CO2 ranges from 170-280ppm. But, <u>they point out this ECS shouldn't be used for projections in our future since we are quite above this low CO2 range</u>**

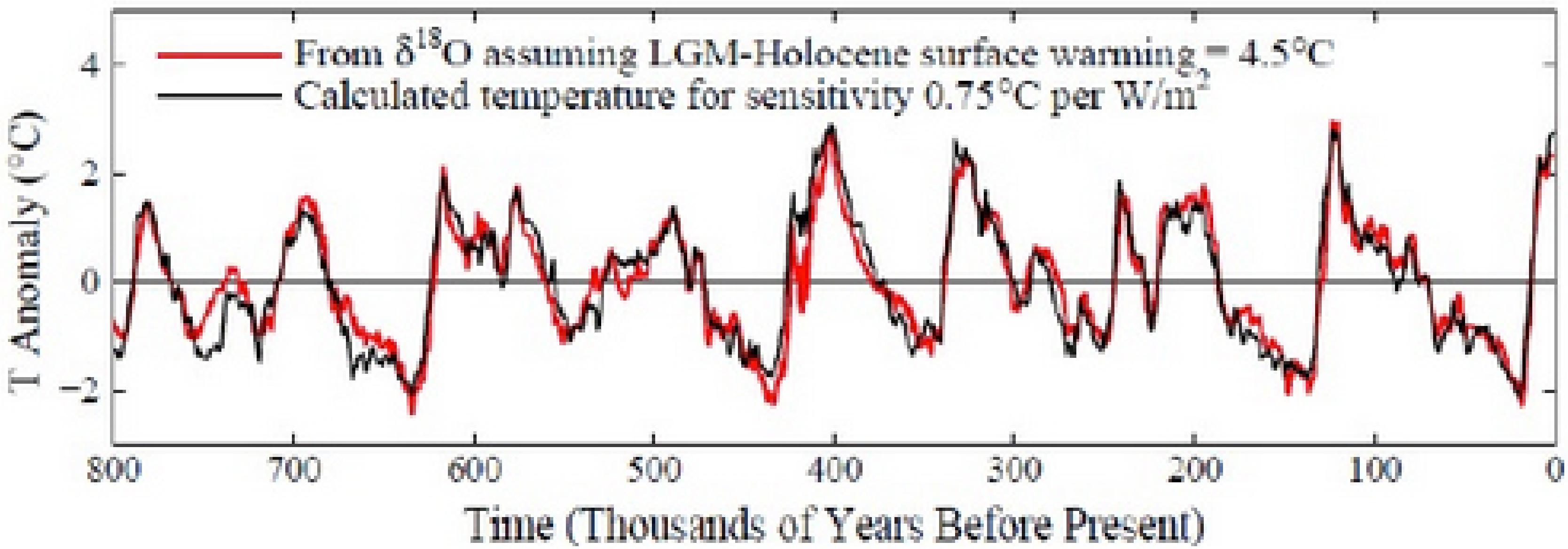



*Figure 3: Black curve: calculated surface air temperature change for climate forcings HS12 and climate sensitivity 0.75°C per W/m2. Red curve: estimated global surface a temperature change based on deep ocean temperatures and assumption th LGM-Holocene surface temperature change is 4.5°C. Zero point is the 800 ky mear Figure 6 from HS12.*

# The different ECS determinations from paleo data may have a simple interpretation

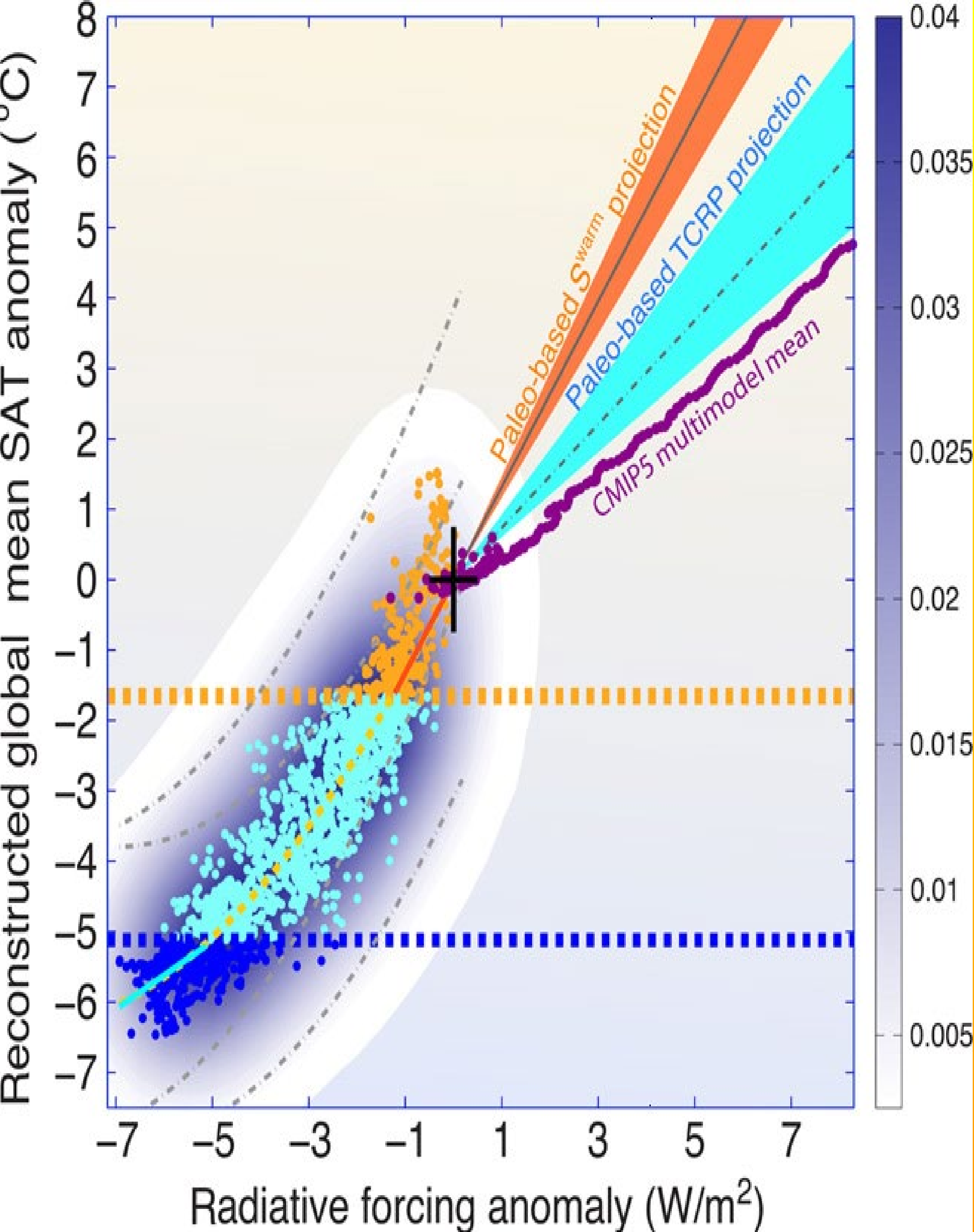
- **ECS** due to CO2 and water vapor alone in a simple Earth system, should be ~constant (the "**band saturation effect**"). But there's no reason to believe that ECS will be constant over the widely differing climate states during the glacial and interglacial conditions of the past million years on the REAL Earth, and especially going forward.
- In paleo data, CO2 is shuttled between the ocean/land and the atmosphere via the solubility, calcareous species, and soil/plant carbon uptake (*e.g*. **Heydt and Ashwin 2016**). This is appropriate going into/out of Ice Ages w/o humans**. But today's CO2 is not coming from the ocean or fast carbon cycle in a ~zero-sum way; we're injecting massive new, previously long sequestered paleolithic carbon into the ocean/land/atmosphere system**.

# We're now melting through the last ice cover of the Arctic Ocean

- …and the powerful albedo feedback will raise temperatures even if CO2 doesn't rise at all.
- Prior to recently, that summer ice was thin but still white and reflective. It's crossed the tipping point of break up and rapidly revealing a dark blue absorptive ocean. Arctic Ocean ice cover didn't transition to rapid drop until year ~2000; quite recently.
- So - not surprisingly - many new studies using the latest climate models and paleo data show significantly higher ECS will very likely apply for our future…

# Friedrich *et al.* (2016) confirm ECS climate sensitivity increases at higher temperatures

- They find a much higher **ECS = 4.88C (4.29 to 5.44C, 1 Std Dev range)** during the interglacial regimes of this period (such as we're in now), **and a very low ECS=1.78C during the deep glacial periods**.
- **This indicates strong positive correlation between ECS sensitivity and global temperature (next slide)**
- This is not only the most detailed of such studies, it is impressive that they find that the average ECS over the entire glacial and interglacial past million years is **ECS=3.22C**. This is in excellent agreement with **Hansen and Sato 2012** and the PALEOSENS work.




**Friedrich *et al.* 2016 Fig 3.** Dots are paleo data: a straight slanting trend corresponds to ECS constant. The strong upward curvature says higher ECS applies at higher temperatures. The orange band assumes **ECS=4.88C** holds today and for the future. However, the orange future slope looks shallower (lower ECS) than the orange paleo data indicate – **meaning, we're entering a new regime. An ECS even higher is quite possible, since ECS=4.9C was what applied during the interglacials of the past few million years, when atmospheric CO2 never got above 280ppm – yet we're at 425ppm now.**

# Friedrich *et al.*'s Figure caption

**Fig. 3 Sensitivity of global mean SAT anomalies to radiative forcing anomalies.**

Scatter diagram (circles) of reconstructed global mean SAT anomalies (K) (**Fig. 2B**) versus net radiative forcing anomalies ($W/m^2$) (**Fig. 2D**) for the last 784,000 years. Anomalies are calculated with respect to PI values. Two-dimensional kernel density estimate of paleo-SAT/radiative forcing data (blue shading). The thick dashed yellow curve represents nonlinear regression of paleo-SAT/radiative forcing data, along with uncertainty ranges (dashed black curves; see Materials and Methods). The thick cyan line represents linear regression for cold phases. The slope represents $S^{cold}$. The thick red line represents linear regression for warm phases. The slope represents $S^{warm}$. Dashed horizontal lines denote warm (orange) and cold (blue) phases using 1 SD of the reconstructed global mean SAT anomalies as a separator. Cold (warm) phases are defined by SAT anomalies of $<-5.12$ K ($>-1.66$ K). The CMIP5 transient model projections using the RCP8.5 forcing scenario are presented by purple circles. Using $S^{warm}$ (orange shading) and taking into account the ocean heat uptake efficiency, we can calculate the transient response to the RCP8.5 radiative forcing. The resulting paleo-based projection with the corresponding uncertainty ranges is represented by cyan shading (see Materials and Methods).

# Is this Apocalyptic Alarmism? No.

- Lead IPCC author Prof. Michael Mann has studied the paper, and conclludes the study is ***"sound, and quite defensible".***
- Friedrich's work shows that on our current trajectory, we're on our way to **+6C by 2100**.
- The result would be severe fraying of civilization, at the very least. Widespread death and industrial breakdown would mean human direct emissions drop significantly before that point.
- **New CMIP6 climate models, ("Wolf pack") for the IPCC AR6, now agree: ECS = +4-5.5C.**

# Will Cloud Feedbacks Amplify Warming, or Not?

- The newer, more advanced GCM's are indicating cloud changes will <u>amplify</u> global average temperatures, but less so after polar ice is largely gone.
- But EMIC's (**E**arth **S**ystem **M**odels of **I**ntermediate **C**omplexity) do not include cloud feedbacks, and it was the **LOVCLIM** EMIC used (with paleo data) by Friedrich *et al.* showing such strongly rising ECS. In fact, after 1000 yrs, most EMIC's show ECS falls, as ice disappears (**Pfister and Stocker 2017**
- **Garrett, Glenn, and Krueger (2018)** **(ArXiv)** claim, on theoretical grounds supported by data, that tropical convective clouds will not show feedback to warmer climate. (But these are NOT the ocean stratus clouds most relevant for climate)
- So at least in these studies, the higher ECS in hotter climates is aided by factors beyond clouds.

# Good *et al.* 2015 Emphasize the Non-Linear Response of Climate to Forcing

- …especially in local and regional climate.
- A simple linear response, (*i.e.* double the cause = double the effect) is, more and more, appearing inadequate to characterize the warming climate we face
- A non-constant ECS is part of this, as paleo data most clearly shows, and which climate models are only beginning to catch up to.
- Remember that climate models' good performance in hind-casts (our Presentation K34) only means that in the early stages of climate change, before dramatic loss of polar ice, for example, that climate non-linearities are small. **That looks very unlikely to remain true going forward.**

# Does the LOVCLIM Model bias ECS to be high going forward?

- **No. Goosse *et al*. (2010, p. 18) find LOVCLIM, upon doubling pre-industrial CO2 but artificially keeping the ice sheets constant, gives ECS of only 1.9C after 1000 years.**
- **So, it suggests it is the ice albedo feedback - very much in the real world – may be what amplifies ECS in LOVCLIM.**
- Remember that for the purposes of our Civilization, it is only the **Fast Feedbacks** to climate which should dominate our immediate thinking and so indeed it is in the conventional Charney definition of ECS (*i.e*. including only the fast feedbacks) which is important for us.
- But it is true that temperatures continue to rise even after the fast feedbacks reach equilibrium.

# Is the LOVCLIM model somehow “hot” among EMICs for some reason? No.

- More recent studies shows it’s right in the middle of a dozen EMIC models in terms of it’s temperature change forecasts over a consistent set of assumptions.

# A New Paper by Steinthorsdottir *et al.* 2020 find ECS must be much higher than standard ECS=3C climate models…

- … in order to explain the high temperatures of the Miocene epoch; +7C hotter than today yet at pCO2 of only ~500 ppm, not far above today's.
- *"A problem remains that climate models cannot reproduce MCO temperatures with less than ~800 ppm $pCO_2$, while most previously published proxies record [that] $pCO_2$ < 450 ppm"*

# And There's Another Reason for a Spuriously Low ECS of only 3C with 20th Century Warming

- Pollution aerosols in cumulus and mixed state clouds is actually nearly **twice as effective** a reflector of sunlight as had been thought (**Rosenfeld *et al.* 2019**) and **erratum**
- *"…It also shows that the heating effect of greenhouse gases is higher than has been thought because it has been mitigated by the impact of aerosols in **clouds**."*

# Consider What This Means

- …Eliminating all FF burning not only reduces $CO_2$ emissions (a climate warmer of course), but also all FF-generated aerosols (which are a powerful climate **coolant** that we now realize has been underestimated).
- **This is therefore consistent with a stronger ECS just as the paleo (pre FF burning) studies I'll show indicate, because higher ECS is being confusingly masked by more effective cooling from aerosol pollution.**

# Kohler *et al.* 2015, using different data and methods, similarly, independently find stronger ECS at higher CO2 and higher temperatures

- **Roughly 45% larger during the interglacial warm periods than during the glacial cool periods, although they don't translate their numbers into an ECS corresponding to a CO2 doubling and so direct comparison is difficult.**
- These studies imply that using only the Ice Age average ECS=~+3C in climate models would substantially underestimate how hot climate will evolve in today's already high CO2 present.

# Shaffer *et al.* 2016 Agree

- They studied the **PETM** (Paleocene-Eocene Thermal Maximum), a geologically brief spike (but still ~100x slower than today's rapid rise rate) in CO2 and temperatures, using new methods.
- They find **ECS = 4.5C** (+-1.1) just before the PETM excursion, and **ECS=5.1C** (+-1.4) into the PETM and conclude ECS rises with increasing temperature. This, despite the fact the Paleocene at the beginning of the PETM was already hot and globally ice-free. No ice albedo feedback involved.
- **We were in an ice-free state even at the beginning of the PETM, yet ECS was already as high as 4.5C. That's disturbing.**

# 8 different studies, different methods, but within each study the trend is *higher ECS at hotter climate* von der Heydt *et al.* 2016 - here as "Sensitivity" S *vs.* deltaT (see Pfister and Stocker 2017 for the ECS connection)

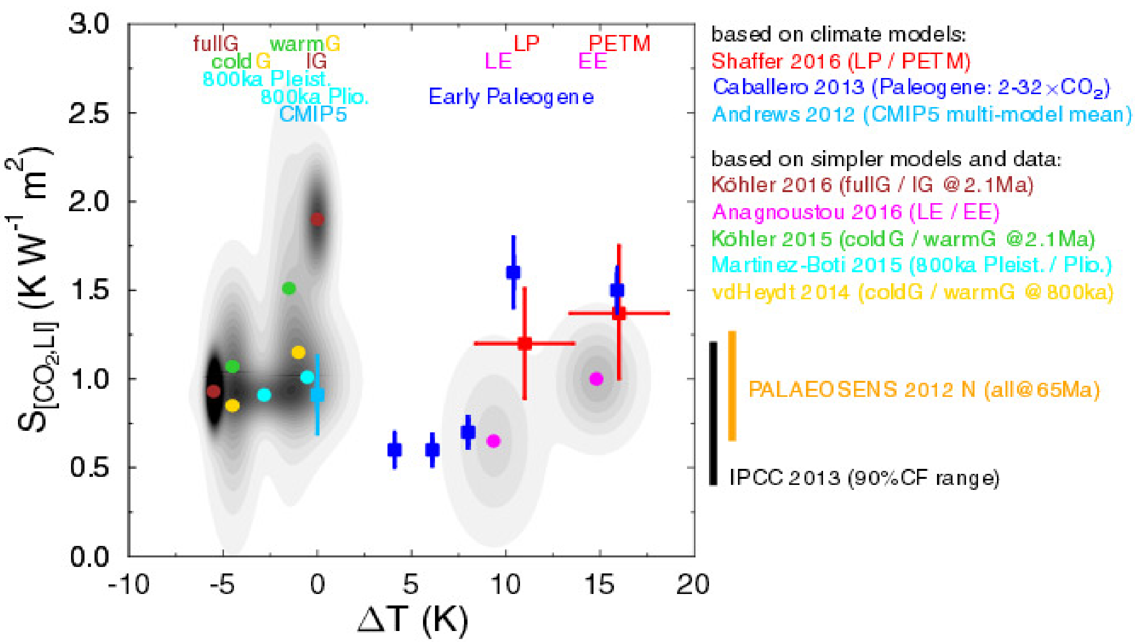
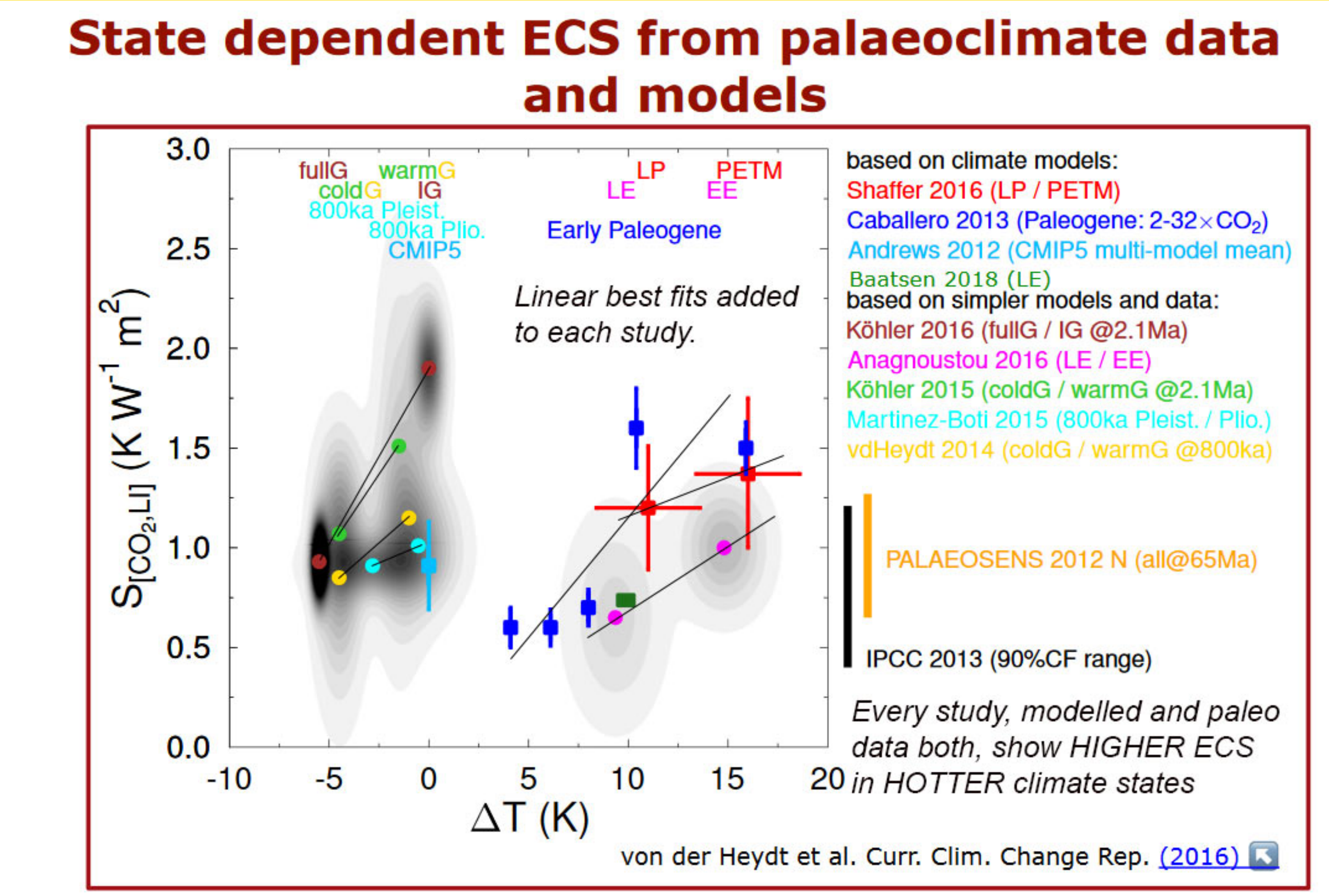



**Fig. 1** Published paleo-based values of $S_{[CO_2,LI]}$ (specific equilibrium climate sensitivity parameter caused by $CO_2$ radiative forcing and corrected by variations in land-ice (LI) feedbacks) indicating its state dependence. Only studies published after the PALAEOSENS review paper [21] are considered. For comparison, the state-independent values from PALAEOSENS, and from the IPCC report [3], and the CMIP5 multi-model mean for present day [41] are also shown. All values of $S_{[CO_2,LI]}$ were given as mean (*or most likely*) $\pm 1\sigma$, apart from IPCC, which is the 90 % confidence (CF) range. Climate background states are given by $\Delta T$ from pre-industrial and are marked as estimated ranges (or $\pm 2\sigma$). In [42], further corrections for other slow feedbacks have been calculated, which has been ignored here, leading to different values of $\Delta T$ than published. To increase the clarity of the figure, the data-based results are visualised by *colour-coded circles* (mean values), while their uncertainties are combined in a cumulative probability density distribution (*grey shading*) assuming normal distributed values. Results based on climate models are shown by *colour-coded squares* (mean) including their uncertainties (*bars*). *G* glacial, *IG* interglacial, *LE* late Eocene, *EE* early Eocene, *LP* pre-PETM/late Paleocene, *PETM* Paleocene-Eocene thermal maximum. Reference numbers of the given citations: IPCC 2013 [3], PALAEOSENS 2012 [21], Andrews 2012 [41], Caballero 2013 [43] vdHeydt 2014 [20], Martinez-Boti 2015 [44] Köhler 2015 [32], Anagnoustou 2016 [42], Köhler 2016 [45], and Shaffer 2016 [46]

# Let's Draw Best Fit Lines Through Each Study's Data. Positive slopes: All show HIGHER ECS in HOTTER Climate States



# The IPCC AR5 Official Range for ECS is too low

- As we'll describe in the **"K44 – Policy"** Presentation, the IPCC process requiring 100% agreement on their AR publications, even from the political representatives, biases "*towards least drama*", and this is clearly reflected in **ECS**, which falls below the values indicated by all of these studies during the warm periods (upper points of the trend lines).

# There is hope the upcoming IPCC AR6 will finally recognize this higher ECS science

- The **CMIP6 models** are showing increased ECS, and the latest and most advanced of the **GFDL** (**Geophysics Fluid Dynamics Lab** at Princeton) climate models is consistent with Friedrich *et al.'s* ECS=4.88C for past interglacial CO2 of ~280 ppm, yet today's 425 ppm.
- Michael Winton, lead GFDL model designer: *"Right now"*, he says, ***"the model's equilibrium sensitivity looks to be 5°C"*** from **this 2019 AAAS article.**

# *“Modelers are struggling to identify which of their refinements explain this heightened sensitivity…*

- *…before the next assessment from the United Nations’s Intergovernmental Panel on Climate Change (IPCC).*
- *But the trend ‘is definitely real. There’s no question,’ says Reto Knutti, a climate scientist at ETH Zurich in Switzerland”.*

# *"The planet is already warming faster than humans can cope with"* – NCAR's Andrew Gettleman

- ***"The scary part is these models might be right, because that would be pretty devastating."***
- I can suggest three places to look for causes of increased ECS: (1) We've found the ocean is absorbing more heat than we thought, and (2) pollution aerosols are making clouds significantly more reflective of sunlight than we'd thought, as we linked earlier (**Rosenfeld *et al.* 2019**) and **erratum** and now similar findings from **Hasekamp *et al.* 2019**, who find the IPCC estimates of radiative cooling forcing by aerosols **was a factor of 2 too low**. And (3), the loss of climate-coolant low stratocumulus clouds over the mid latitude oceans. More later on this.

# Indeed, NCAR's latest models…

- …with improved aerosols but using a too-low ECS found that the aerosol cooling effect **nearly cancelled out all 20th century global warming**(!)
- Yet, the **20th century most certainly DID warm.** How to explain that? …
- It requires **higher** ECS than they assumed, to make consistent with **actual** 20th century warming.

# Let's do a simple back-of-envelope estimate of ECS to justify these higher new estimates…

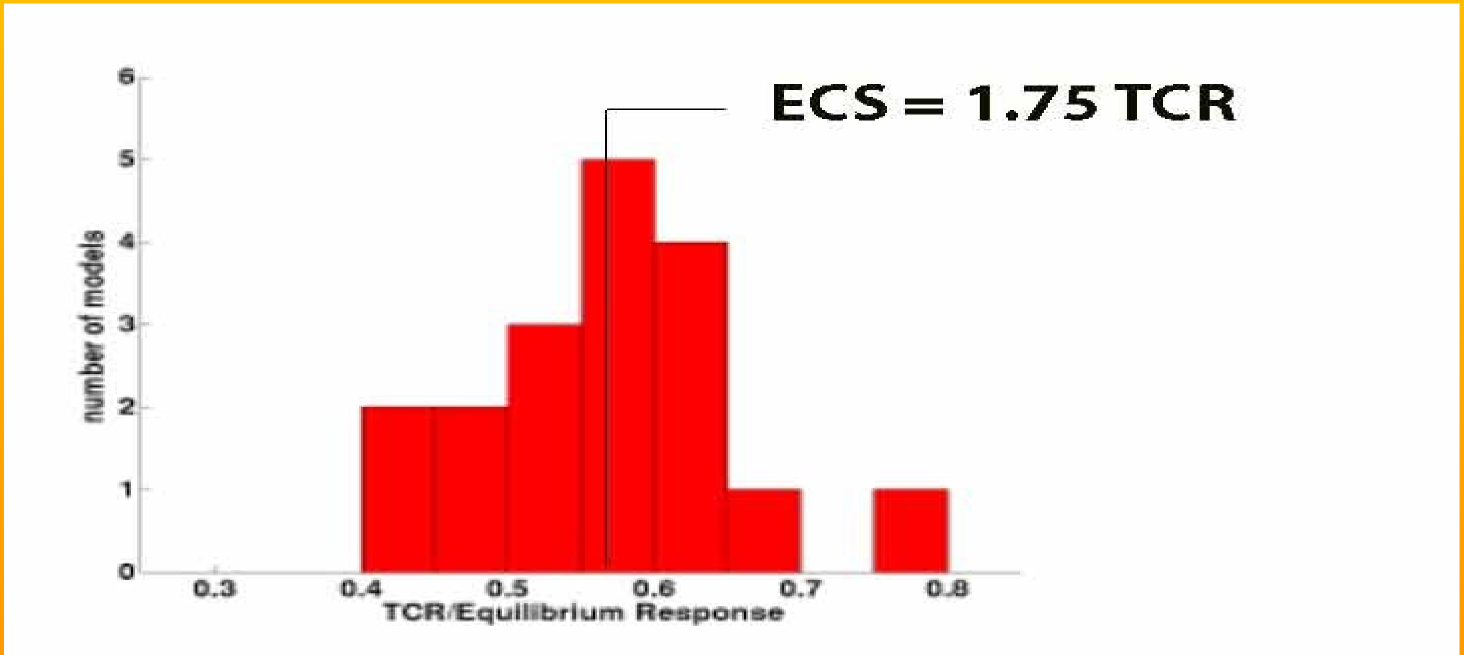
- As of 2020, we are at +1.48C above the best (**Schurer, Mann *et al.* 2017**) new estimate of the Pre-Industrial temperature baseline (not the conventional ~<1880-1910> baseline).
- CO2 concentrations in 2020 were at 415 ppm, or 48% of the way to a formal doubling of the 280 ppm pre-industrial baseline.
- Therefore…

# A Simple Linear Extrapolation…

- Then gives transient climate sensitivity (=TCR =*T at the moment we cross 2xCO2 = 560ppm*) of **+3.1C**. But that's not yet equilibrium, so ECS will sail higher until levelling off, decades further into the future, at fixed 560ppm of CO2.
- But this is certainly an underestimate of even just TCR: Why?
- **1.** It is only in the past 20 years that the Arctic Ocean ice cover has begun retreat, then melted through, strongly increasing the ice albedo feedback.
- **2.** Methane is rising much more steeply than CO2 and is roughly 1/3 of climate forcing. Methane is 300% of pre-industrial values, while CO2 is only 148% of pre-industrial values
- **3.** Cloud feedbacks are poorly determined, but increasingly look to add further to this, especially low cloud losses.

# But even taking the low-ball 3.1C as TCR

- TCR/ECS ~1.75 (here) or 2.1 (Schwartz 2011)
- Even using the lower value, converting to ECS gives 1.75 x 3.1C = **ECS = ~+5.4C**
- …which better aligns with the CMIP6 values of ~+5C, and the Friedrich *et al.* 2016 value of +4.9C.



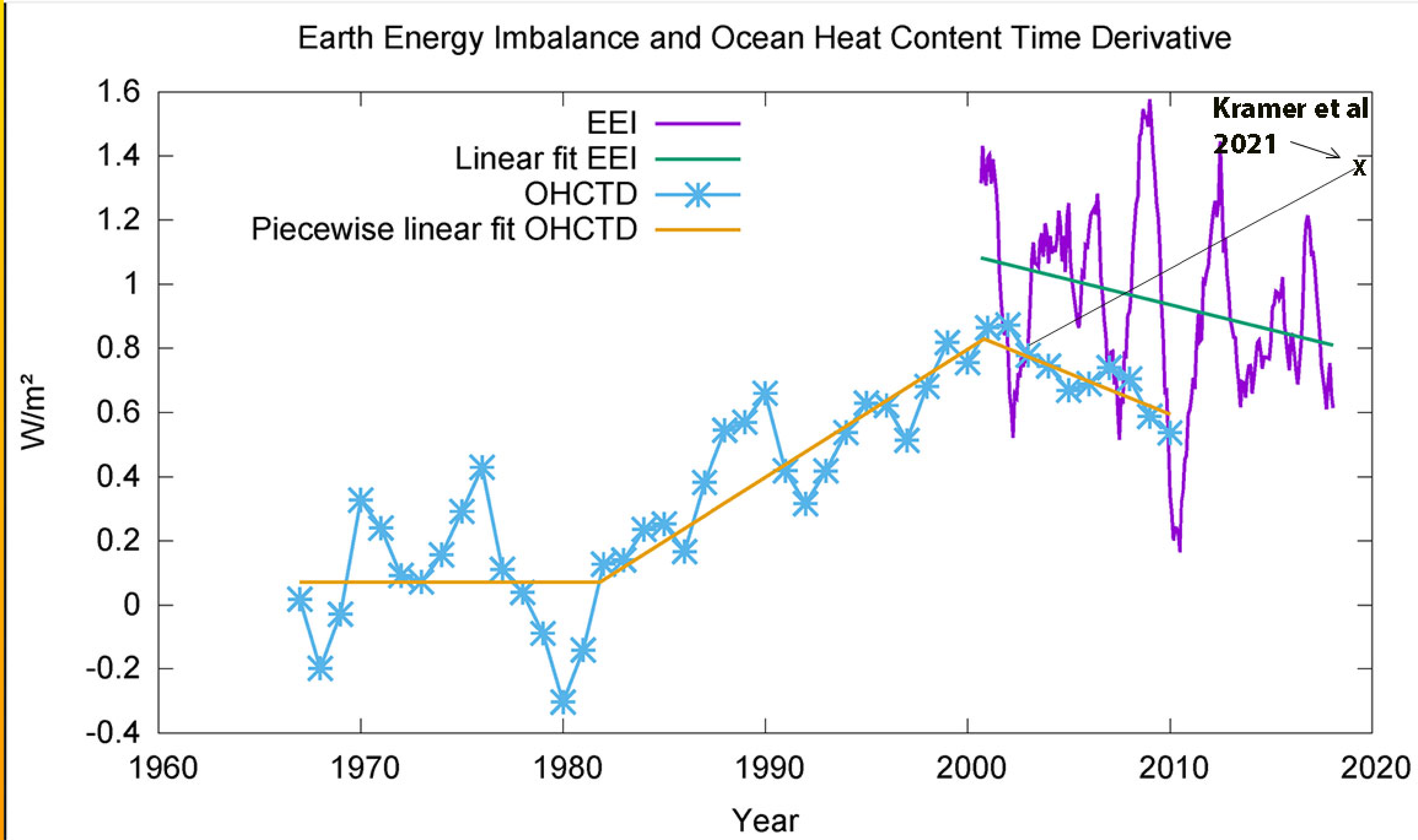
# Earth is Not in Radiative Equilibrium

- We are forcing it to higher temperatures by continually increasing the atmosphere's thermal resistivity by adding CO2 and raising humidity. If we merely STOP forcing the resistivity higher (constant atmos CO2), the surface will still not be in equilibrium.
- It will take a century or more until the atmosphere and land/ocean surface is hot enough to again be radiating almost as much heat as we get from the sun.
- During that time, we are doomed to further heating. That heating can be either rapid, or slow, depending on our actions – **<u>but warming will continue.</u>**

# The Earth is (was) able to continuously radiate 0.58* watts/m$^2$ less than it receives from the sun

- … the canonical value, averaged over the entire Earth as of the early 2000’s decade. How much heating is that?
- Imagine every person on Earth has 42 (the answer to the Universe number!) additional arms and hands, and in each hand is a 1000 watt hair dryer, and they run that hair dryer 24x7x365, continuously. That’s 0.58 watts/m$^2$
- *And a newer 2018 study says this is significantly higher: **0.83 watts/m$^2$**
- But wait – it’s worsening…

**Newer: From Dewitte *et al.* 2019 combined with Kramer *et al.* 2021. The Earth's energy imbalance has increased an additional 0.53 watts/m² just in the 2003 – 2018 interval due mainly to rising GHG's and falling aerosol pollution, *giving a net current ~1.38 watts/m² radiative imbalance**



# Now in 2023, Earth Energy Imbalance (EEI) is Much Higher, at 2 W/m$^2$

- It is this measure - EEI - which is directly correlated to the rate of global temperature rise
- From **Hansen *et al.* 2023**

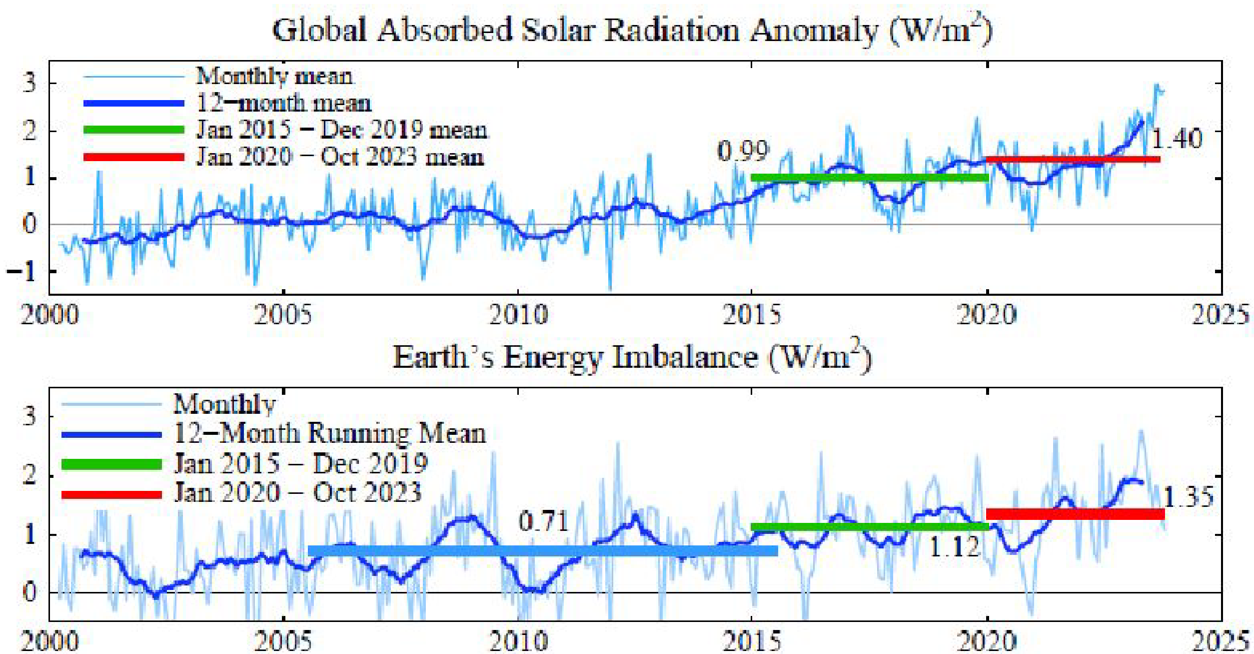
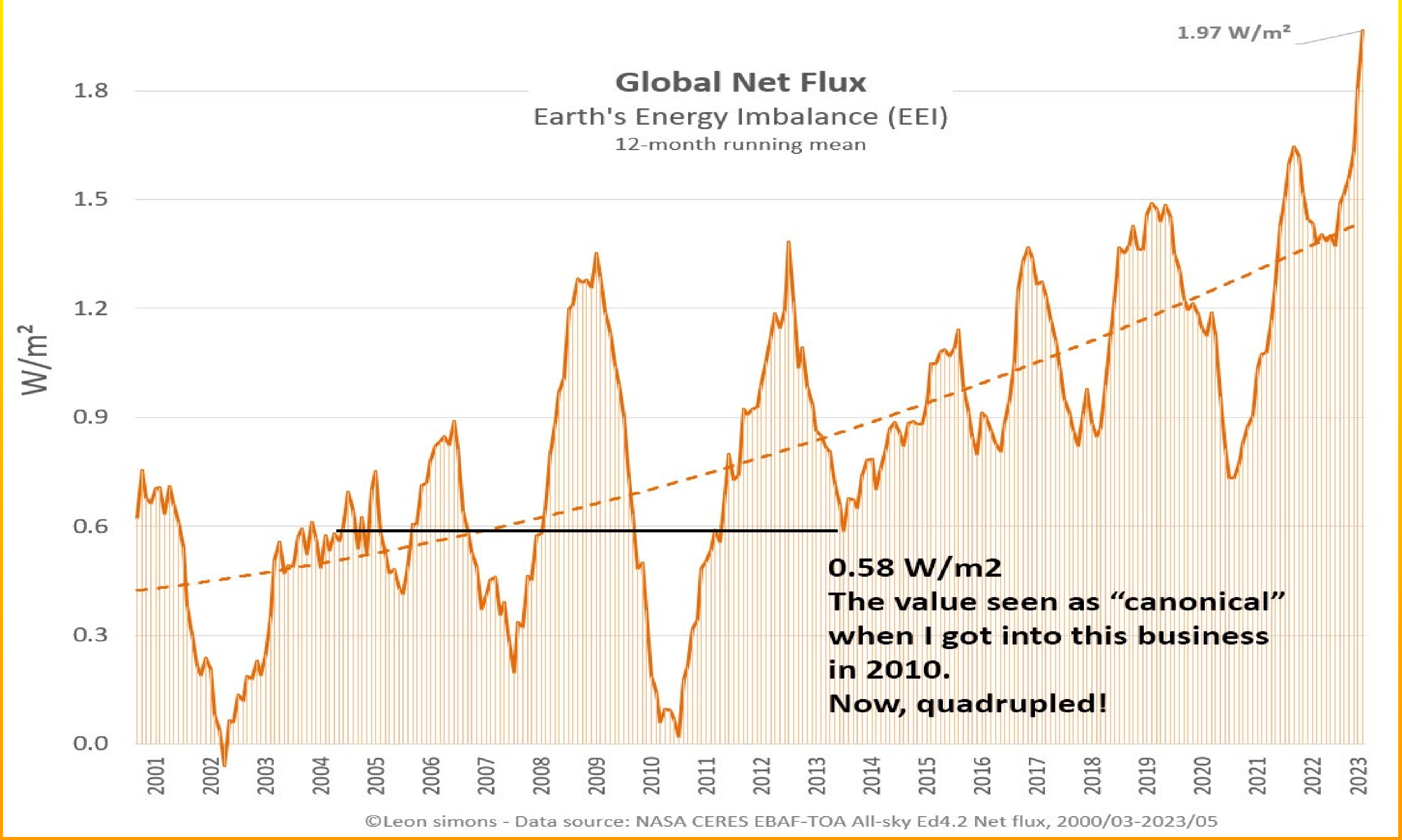
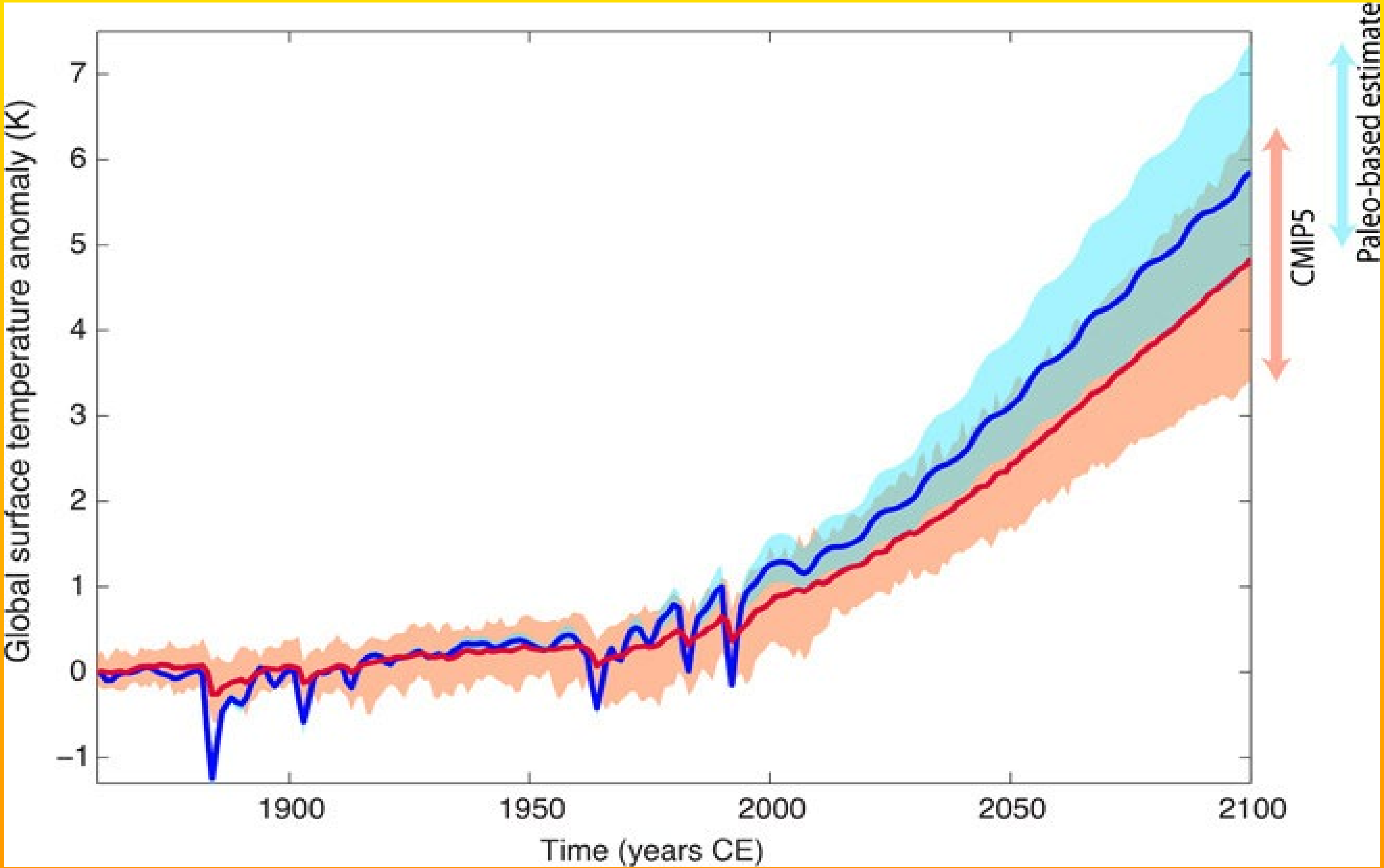



**Fig. 4. Global absorbed solar radiation and Earth's energy imbalance relative to the mean of the first 120 months of CERES data. CERES data[10] are available at http://ceres.larc.nasa.gov/**

# Earth Energy Imbalance (EEI) has accelerated in recent years



**Under "Business as Usual" (+4C at 2100 CMIP5), the Friedrich *et al.* (2016 Figure 4) paleo study (blue) gives temperatures +6C above pre-industrial, and rising. This would be cataclysmic, resulting in a steeply collapsing civilization.**

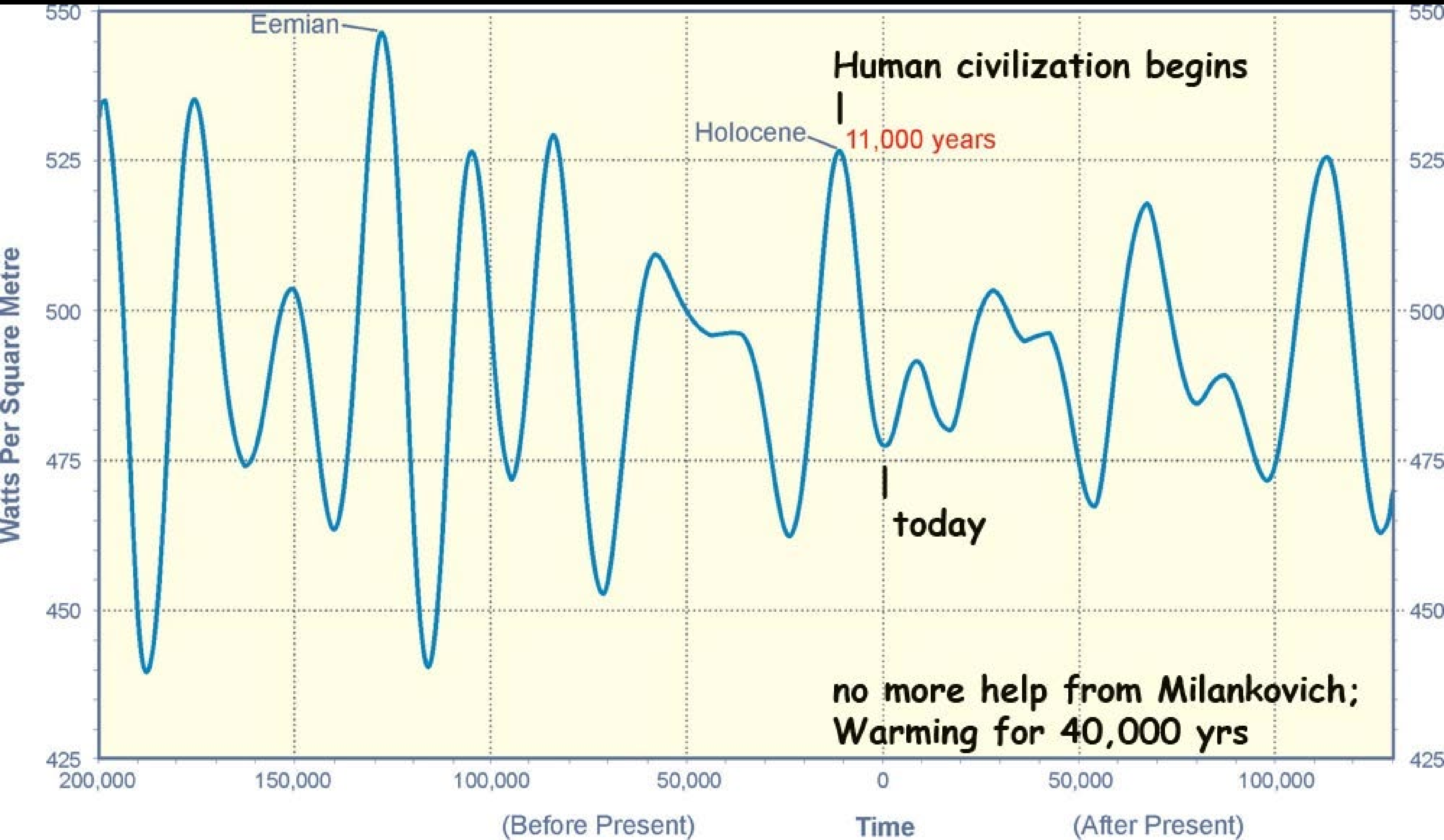


# 3. The Irreversibility of Climate Change

- For climate to stabilize, anthropogenic carbon emissions must be **reduced to zero, and then well below zero**. Until then, temperatures continue to rise (Matthews and Caldiera 2006)
- And because of the large thermal capacitance and inertia of the oceans, the time scale for final planet-wide equilibrium to come back down to temperatures of just a few decades ago, **is tens of thousands of years (next slides).**

- For all of human civilization's 10,000 year history, Nature has been helping offset our small (until now) heating effects by Milankovitch cooling… (remember the Milankovich Cycles…? The effect of summer melting of winter's ice at the Arctic Circle, preventing Ice Ages, ruled by oscillations in Earth's tilt, orbit, and orientation).

# Milankovich Cycle: in Cooling Phase During all of Human Civilization… But Is Now Maximum and Will Reverse Soon.



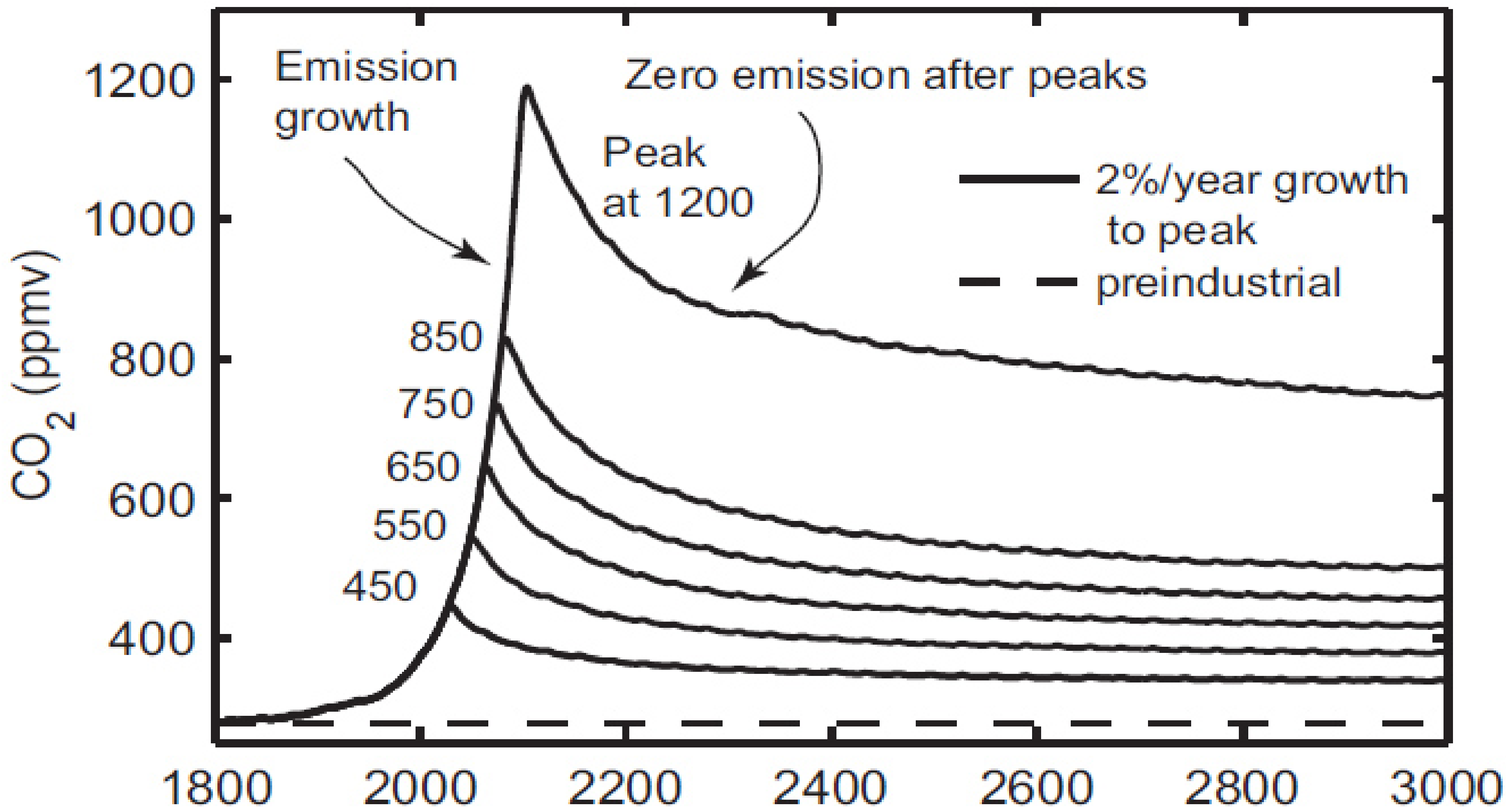
Let’s now look at rosier but less informed earlier predictions of future temperatures from studies published over a decade ago – studies which had assumed that ECS was not state-dependent and was only +2C or +3C.

They are still sobering…

# CO2-Induced Climate Change is <u>Irreversible</u> for Thousands of Years

- **Solomon *et al.* 2009** , **Port *et al.* 2012** and others, show that CO2 added to the atmosphere is only very slowly soaked up by the oceans and land, and ocean's thermal mass and inertia (**700x the thermal mass of our atmosphere**) mean that climate change is **irreversible on any human time scales.**
- Newest study says **<u>tens of thousands of years before climate could return to pre-industrial conditions</u>, this is long past when Milankovich forcing will produce warming for astronomical reasons.**
- It is probably worse… Solomon *et al.* uses IPCC AR4 2007 climate models as starting points. These are, as we know now, overly optimistic. They also **do not include permafrost and peat release of methane, nor continental glacier acceleration due to meltwater at the base, nor iceberg travel south out of the Arctic Ocean. Nor inhibition of warmer, fresher water near the melting poles to penetrate the thermocline, nor albedo changes to polar ice, and other effects**
- One caveat – in an interview, Solomon acknowledged that **if somehow CO2 could be pulled OUT of the atmosphere on a grand scale, this would be a solution, if it were done soon enough, massively enough, before too much CO2 diffused into the oceans.**
- Figures from Solomon *et al.* 2009 on the next page…

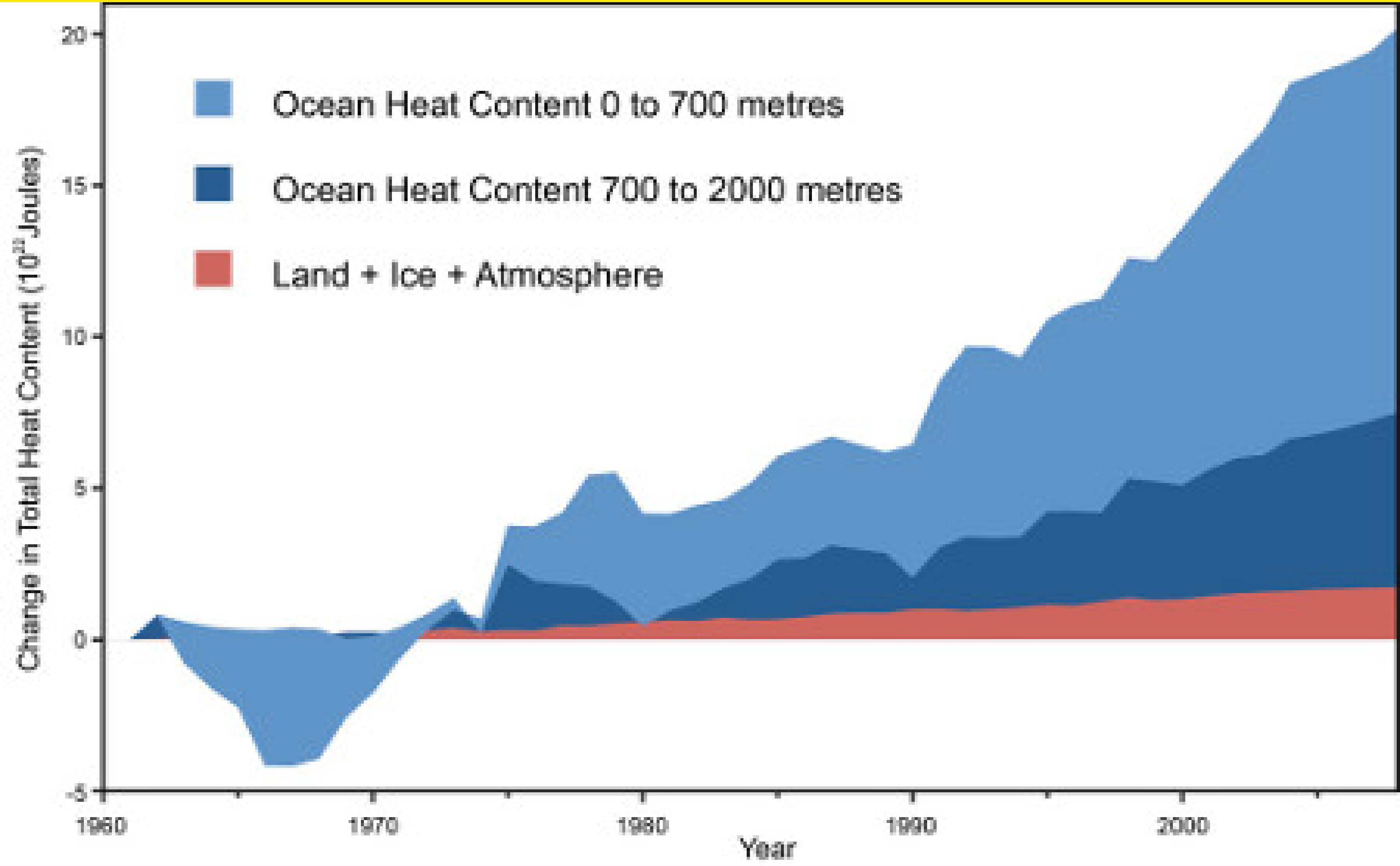
**From Solomon *et al.* 2009. Atmospheric CO2 – Next 1,000 years. Assumed "Business as Usual", then instant 100% end of CO2 emissions. CO2 only slowly declines over the next ~200 yrs, then levels out. (These post-emission declines however do not include the now better-understood destruction of soil microbes and the inability of plants now in existence to handle such climate change and sequester the same carbon, and are too optimistic).**



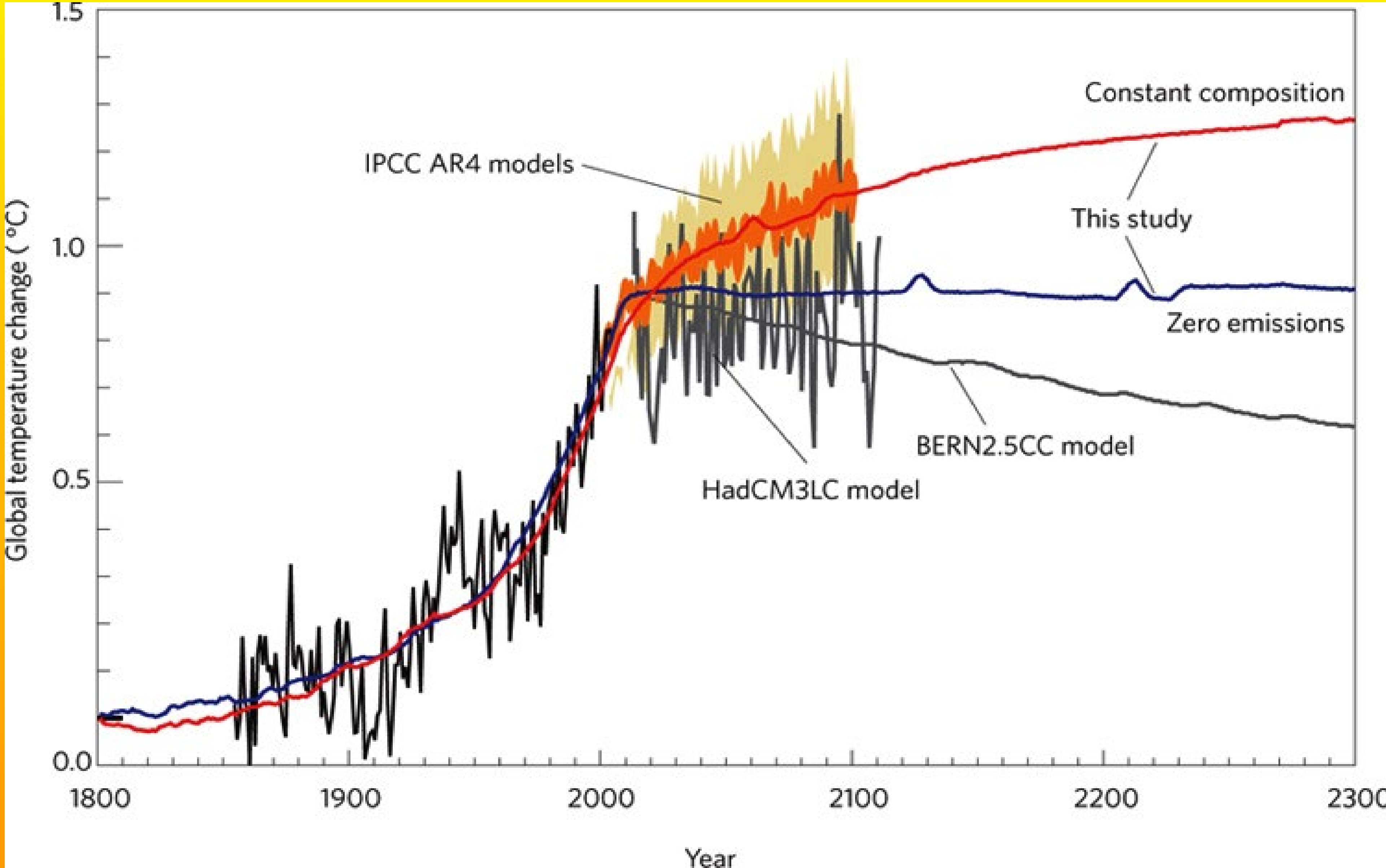
# Why Don't CO2 Levels Fall Faster when Emissions Stop?

- **Because on a warmer planet…**
- **1.** CO2 does not absorb well into a hotter ocean – a hotter ocean can hold less dissolved CO2
- **2.** The sheer time scale of mixing CO2 into the ocean. Complete ocean mixing takes ~1,000 years.
- **3.** Thermal inertia of the oceans. Remember, we saw that **93% of the heat of global warming has gone into the oceans**. That heat won't go away, it's still there, and being added to every day.
- **4.** Marine plants and animals are significantly less able to convert dissolved CO2 to CaCO3 under **rising acidity**

# 93% of our Greenhouse heating has gone into the oceans, where, even in the best cases, it will radiate away only extremely slowly



**Therefore, temperatures don't fall. From Matthews and Weaver (2010) with explanation here. With better biology included, show that even with ZERO GHG emissions, temperatures at best remain constant (except with the BERN2.5CC model, which includes substantial human-induced atmospheric CO2 removal).**



# Conclusions from Solomon *et al.* 2009

- *<u>"Anthropogenic Global Warming is irreversible for more than ~1,000 years after emissions stop.</u>*
- *"Following cessation of emissions, removal of atmospheric carbon dioxide decreases radiative forcing, but is largely compensated by slower loss of heat to the ocean, so that atmospheric temperatures do not drop significantly, even out 1,000 years into the future" (after which they stopped calculating.)*
- *"If atmospheric carbon dioxide concentrations increase from current levels near 385 ppmv to a peak of 450–600 ppmv over the coming century, leads to irreversible dry-season rainfall reductions in many regions (including western U.S.) comparable to those of the ''dust bowl'' era, and inexorable sea level rise."*
- ***(Solomon's work is now 15 years old. CO2 today is 424 ppm – 2024)***

# But Won't CO2 "Fertilization" Sequester More Carbon, Looking on the Happy Side?

- Port *et al.* (2012) model effects on vegetation from predicted CO2 rises. Plants use CO2 for the carbon.
- They find fertilization due to rising CO2 causes boreal forests to spread north, deserts to slightly shrink but move poleward.
- **But including the rise in carbon sequestered by CO2-fertilized plants, the resulting added reduction in greenhouse warming is found to be only 0.22 C.**
- 0.22C drop, however, is only a tiny dent in the net ~4 to 6 C rise in the global temperatures they consider.

- And studies in 2013 say this is probably too optimistic, since it fails to include the effect of heating and drying on the soil microbes which fix nitrogen so that it is available to plants… Most plants are nitrogen-limited, not carbon-limited
- It also fails to account for the rapidly rising boreal and temperate forest fires as droughts spread. Burning forests convert sequestered carbon into atmospheric carbon
- And finally, new work by Wang *et al.* (2020) show that the "CO2 Fertilization Effect (CF)" is being crippled by climate change. **They find the reduction in CF by almost 50% since 1980.**

# From Port *et al.* 2012. Again CO2 drops (top), but not temperatures (bottom left)

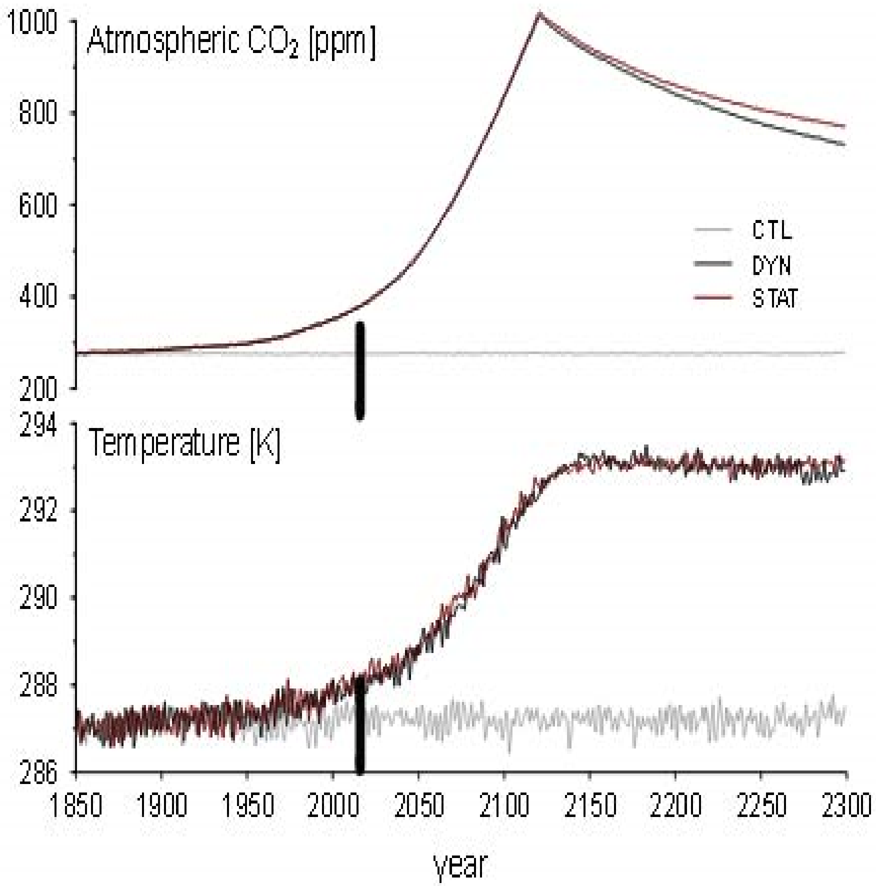



**Fig. 2.** Time series of annual mean atmospheric $CO_2$ concentration and global annual mean temperature in the CTL (grey line), the DYN (black line), and the STAT (red line) simulation.

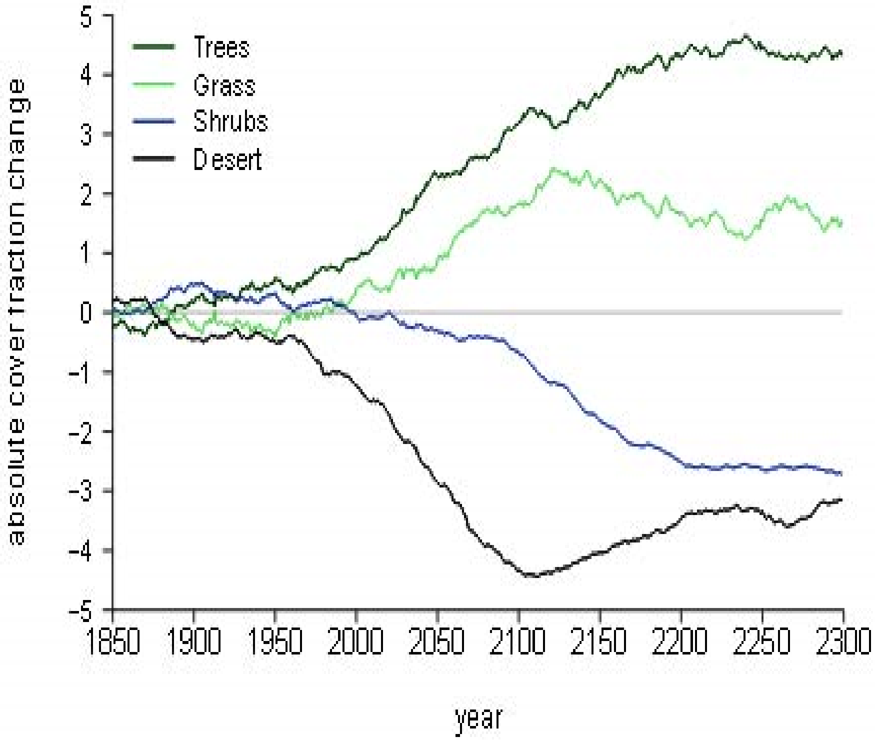



**Fig. 3.** Time series of changes in absolute global mean vegetation cover (DYN – CTL) in [%]. Forest includes tropical evergreen and deciduous trees as well as extra-tropical evergreen and deciduous trees. Shrubs contain cold and rain green shrubs and grass includes $C_3$ and $C_4$ grass.

# But what if the newer work of Friedrich *et al.* 2016, Kohler *et al.* 2016 and Hansen *et al*. 2023, and the new CMIP6 climate models, all indicating a higher ECS, are correct?

- This would be a profoundly important and dangerous situation with far-reaching consequences:
- **Indirect human-caused carbon emissions become unstoppable, even if all human-generated carbon emissions cease** (**MacDougal *et al.* 2012**).
- **They find that for ECS higher than +3.0C, the Permafrost Carbon Feedback** is initiated and the tipping point already crossed. More on this later…

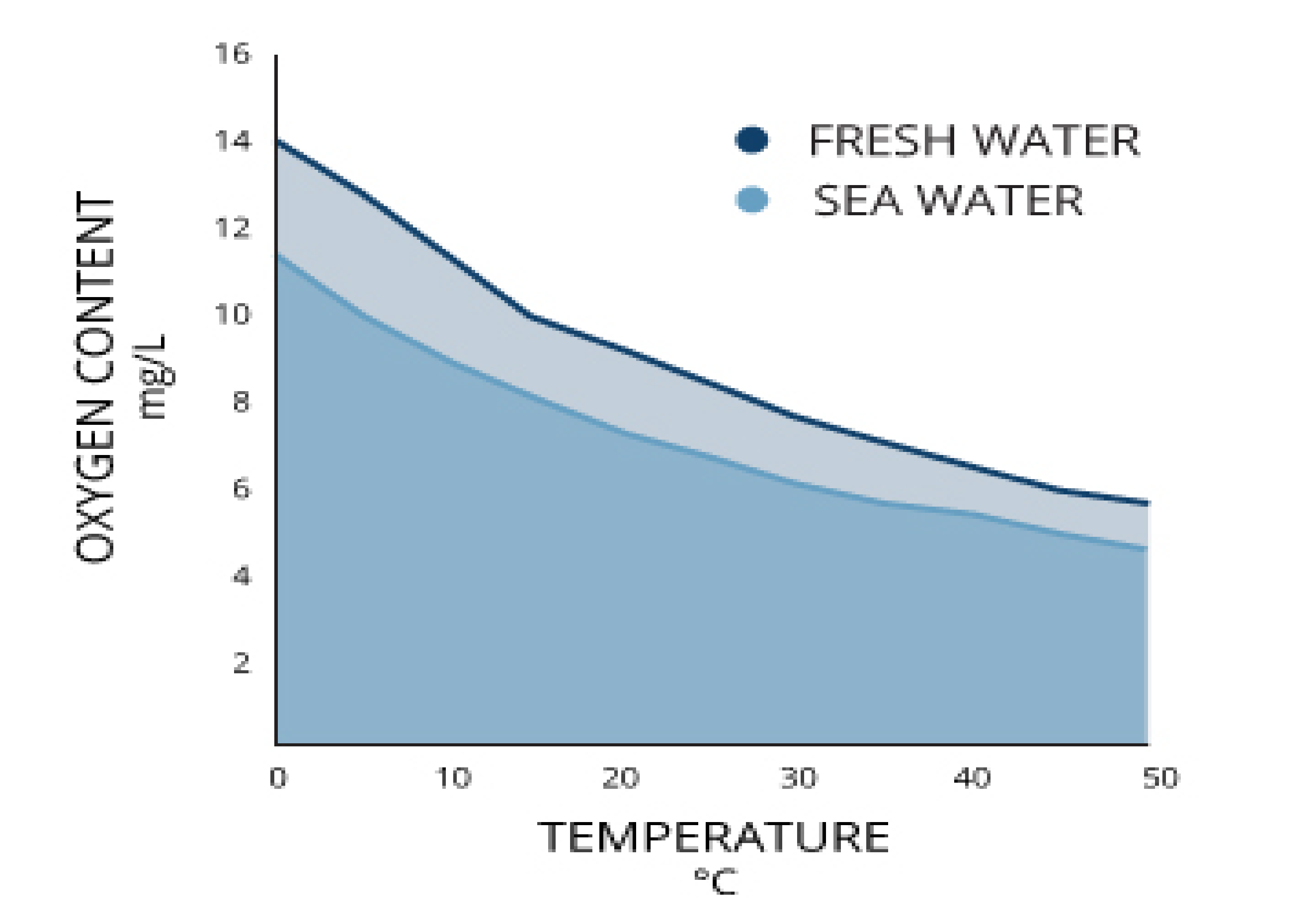
# Irreversible Ice Sheet Loss

- The entire Antarctic Ice Sheet is also at risk of irreversible loss.
- **Garbe *et al.* (2020 in Nature**) show that once the tipping point is crossed, sometime in the next 100 years, the cryosphere is irreversibly lost. Hysteresis in the system.
- Even somehow returning to pre-industrial temperatures will not bring it back.
- Why? The albedo and altitude feedbacks require a much **colder** Earth to permit re-ice.

# 4. Dropping Oxygen Levels

- … in the ocean and in the atmosphere. We're already seeing this, and expect it to continue.
- Oxygen loss in warming oceans will hinder carbon fixation by phytoplankton.
- Favors the ocean ecosystem takeover by jellies, which need little oxygen, and dis-favors fish, which are high-energy oxygen-breathing animals.
- **This article** from **the American Geophysical Union** says widespread oxygen loss in the ocean will be obvious by 2030.
- Due to solubility physics, dissolved oxygen in the ocean drops by **2% for each 1 C temperature rise**

# Oxygen saturation, in salt and fresh water, drops with increasing temperature. This is pure physics, and is on top of the declining oxygen <u>production</u> due to stressed phytoplankton and carbon burning

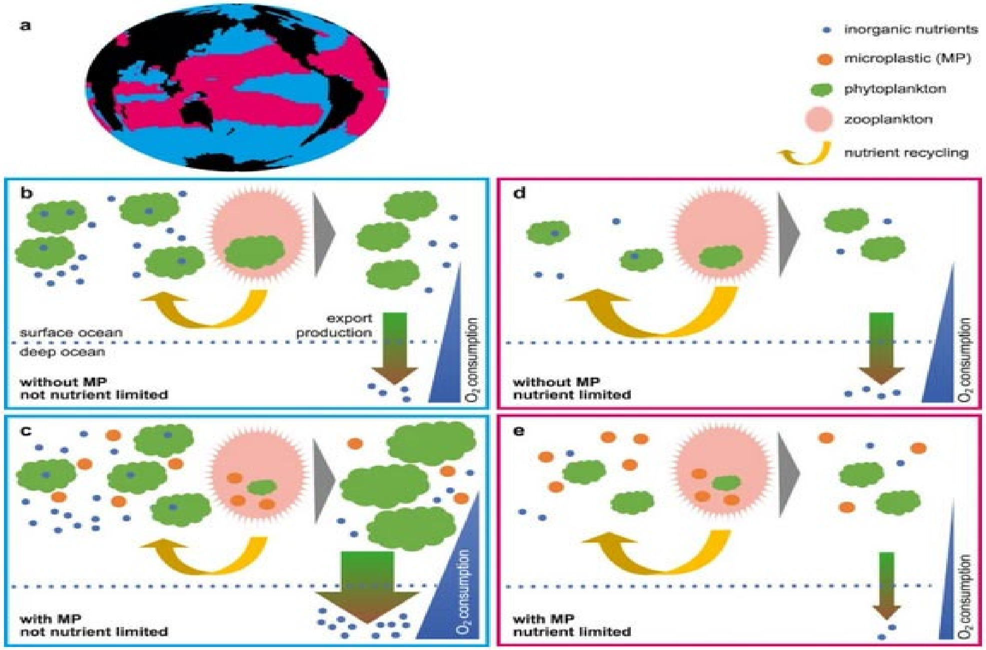


# But in fact - ocean oxygen levels are dropping 2x-3x faster than this, and faster than our models predicted

- *"Depletion of dissolved oxygen in our oceans, which can cause dead zones, is occurring much faster than expected, a new study finds. And by combining oxygen loss with ever-worsening ocean warming and acidification, humans are re-creating the conditions that led to the worst-ever extinction, which **killed over 90 percent of marine life** 252 million years ago." (Scientific American **May 2017**)*
- *"2015 study **found** there is no techno-fix to prevent a catastrophic collapse of ocean life for centuries, if not millennia, if we continue current CO2 emissions trends through 2050. If we don't start slashing carbon pollution, then, as co-author John Schellenhuber put it, '**we will not be able to preserve ocean life as we know it.**'"*

# Now a New Mechanism Causing Anoxic Oceans: Microplastics

**Fig. 3: Schematic of impact of zooplankton ingestion of microplastic on water column dissolved oxygen.**

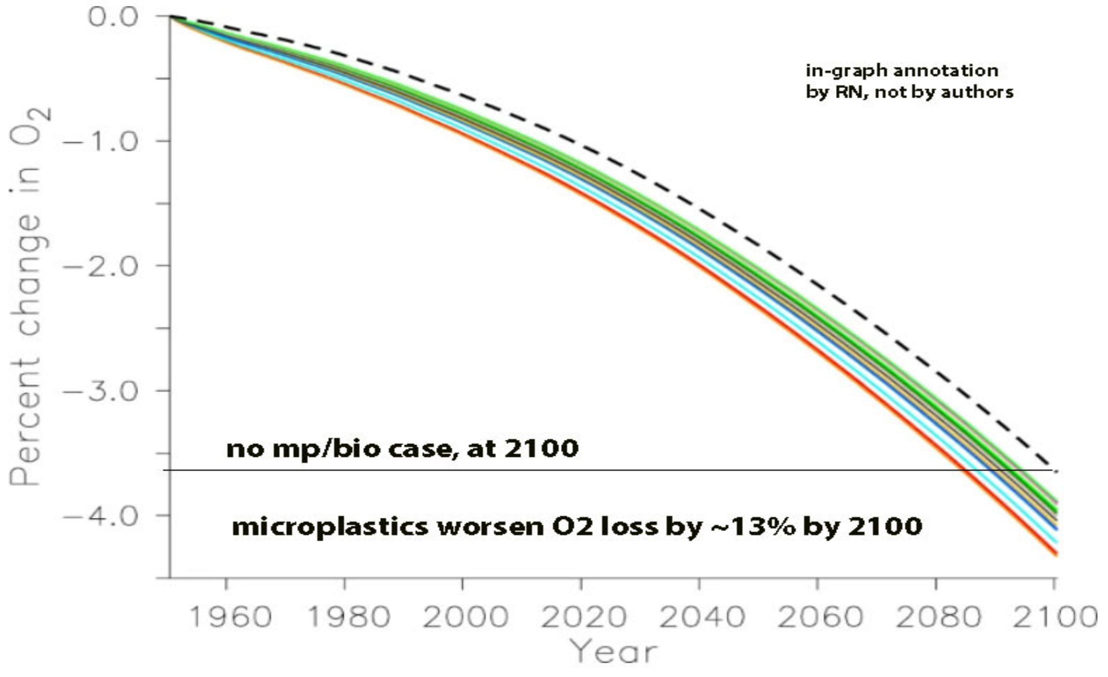



**a** Map view of macronutrient limited (pink) and nutrient-replete regions (blue). **b** In macronutrient-replete regions, e.g. the Southern Ocean, grazing pressure from zooplankton is a significant control on primary and export production. **c** Consumption of microplastic by zooplankton in macronutrient-replete environments reduces the grazing pressure on primary producers enhancing export production, that upon remineralization at depth consumes oxygen. **d** In macronutrient-limited environments primary producers rely on recycled nutrients supplied via the microbial loop and zooplankton excretion. **e** In the presence of zooplankton ingestion of microplastic a greater proportion of nutrients cycles through the temperature-sensitive microbial loop, leading to a decrease in export production which in turn drives a reduction in oxygen consumption at depth for remineralization.

- Zooplankton ingestion of **microplastics (MP)** causes a net increase in the re-mineralization of the MP's, consuming dissolved oxygen from the ocean. Kvale *et al.* 2021

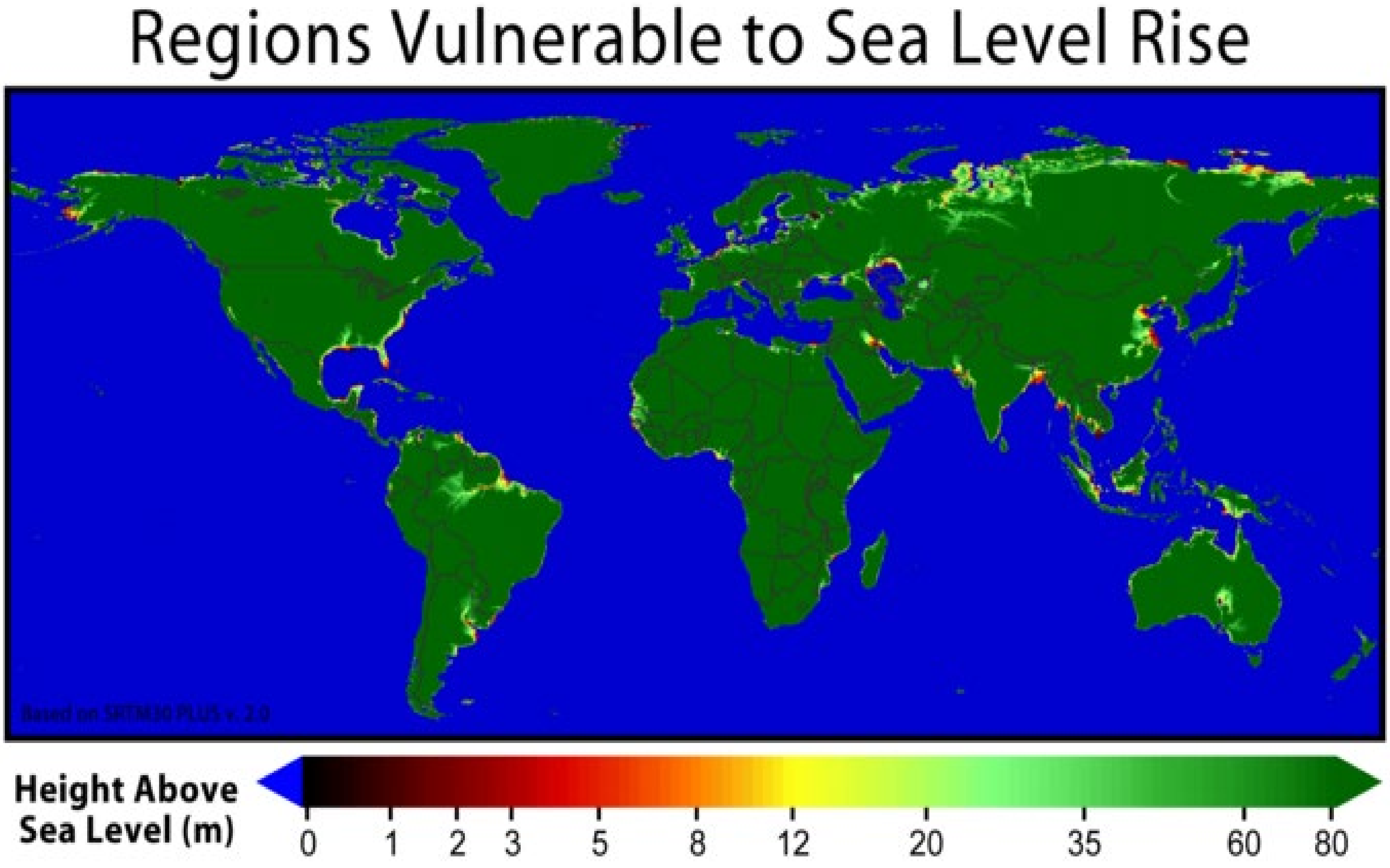
**MP's worsen oxygen loss by an additional ~13% by year 2100 *vs.* prior models w/o MP's considered. This mechanism has no paleo data precedent. Relevant for predictions depending on paleo data.**

**Fig. 8: Timeseries of change in global oxygen inventory normalized to value at 1960.**




The No Bio simulation is represented as a dashed black line, and the rest are the suite of 14 simulations that include biological interaction with microplastic, selected from a 300 member perturbed-parameter ensemble[7] that searched the parameter space of the model to find the most plausible microplastic uptake parameter combinations.

# 5. Future Sea Level Rise

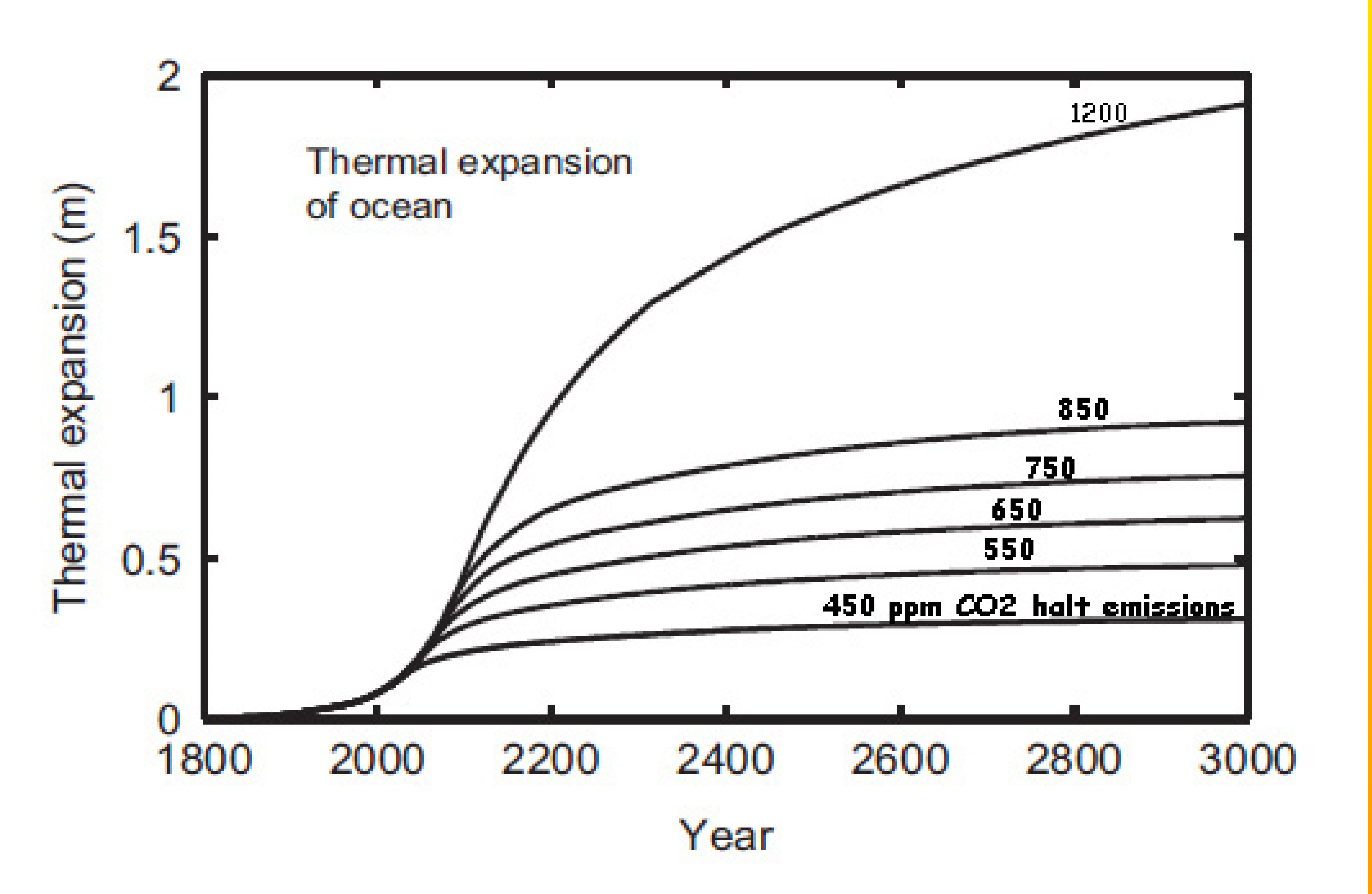


# Solomon *et al.* 2009 conclusions, continued

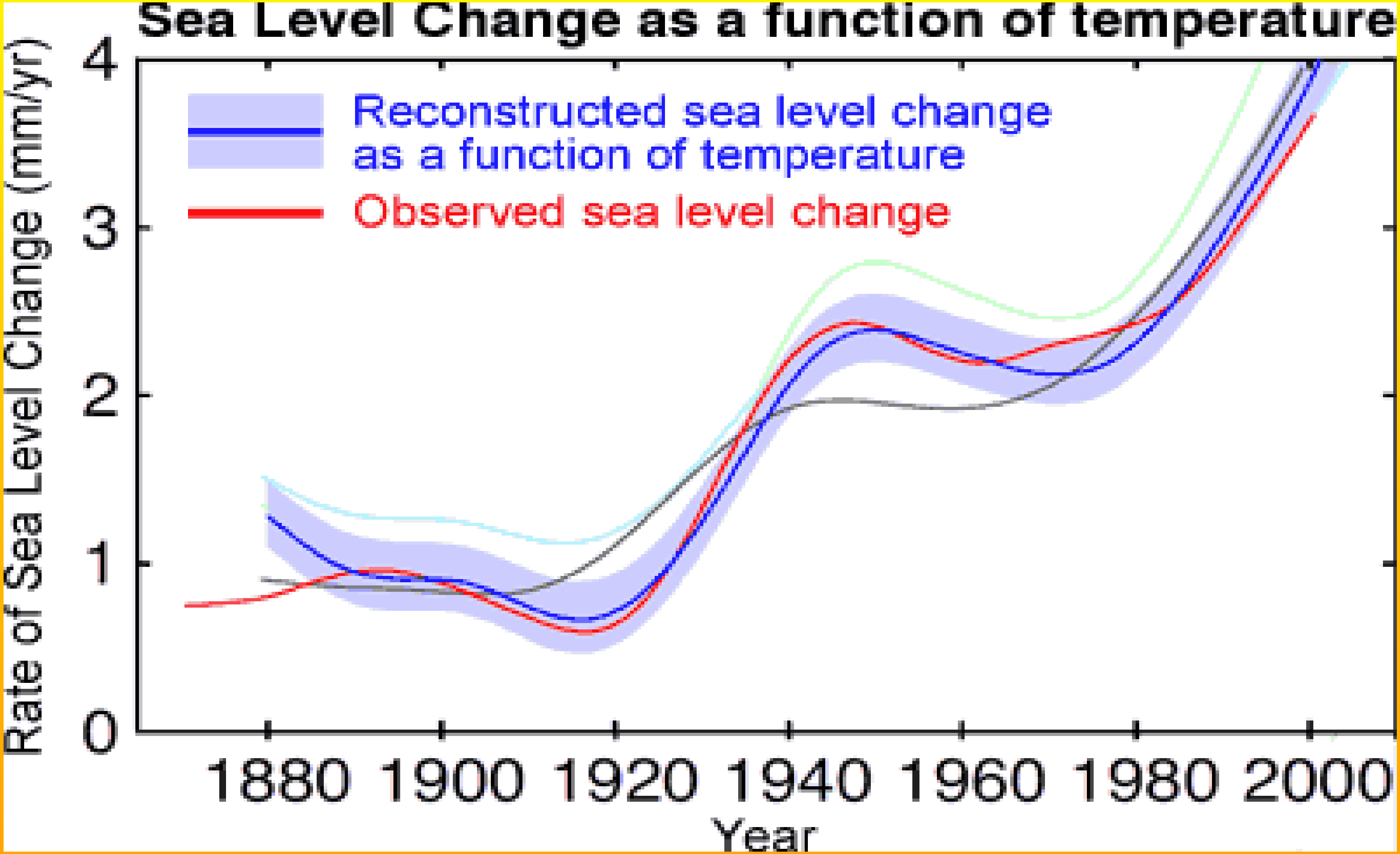
- *Thermal expansion alone, even neglecting melting of continental ice, produces irreversible global average sea level rise of at least 0.4 –1.0 m if 21st century CO2 concentrations exceed 600 ppmv and 0.6 –1.9 m for peak CO2 concentrations exceeding 1,000 ppmv. Sea level rise does not stop there, it continues to rise.*
- *Additional contributions from melting glaciers and ice sheet contributions to future sea level rise are uncertain but may equal or exceed several meters over the next millennium or longer.*
- *Actually, the authors advise that their modelling "*does not include changes in the earth's uptake of heat due to ice melting and vegetation changes. Thus the model significantly underestimates the irreversibility of the climate system" ( source).

- *These findings (and worse) are confirmed by Port et al. (2012), Wigley and Weaver (2010) and others*
- *In '12 - After the work of Rahmstorff on polar ice melt, these sea level predictions look much too conservative, and sea levels may rise well more than a meter before the end of this century*
- *New in '14 - the discovery of the now-begun collapse of the West Antarctic Ice Sheet means 10+ ft of sea level rise from this source alone)*
- *Glacial melt, we are now learning, is a very non-linear process*

**This graph considers <u>thermal expansion of ocean water only,</u> corresponding to the CO2 emission scenarios shown earlier. But temperatures held this high for this long will cause much of continental land ice to melt, adding increasing sea level <u>several times more than shown here</u>**



# The Rate of Sea level Rise Itself continues to Accelerate as Land Ice Melting Accelerates

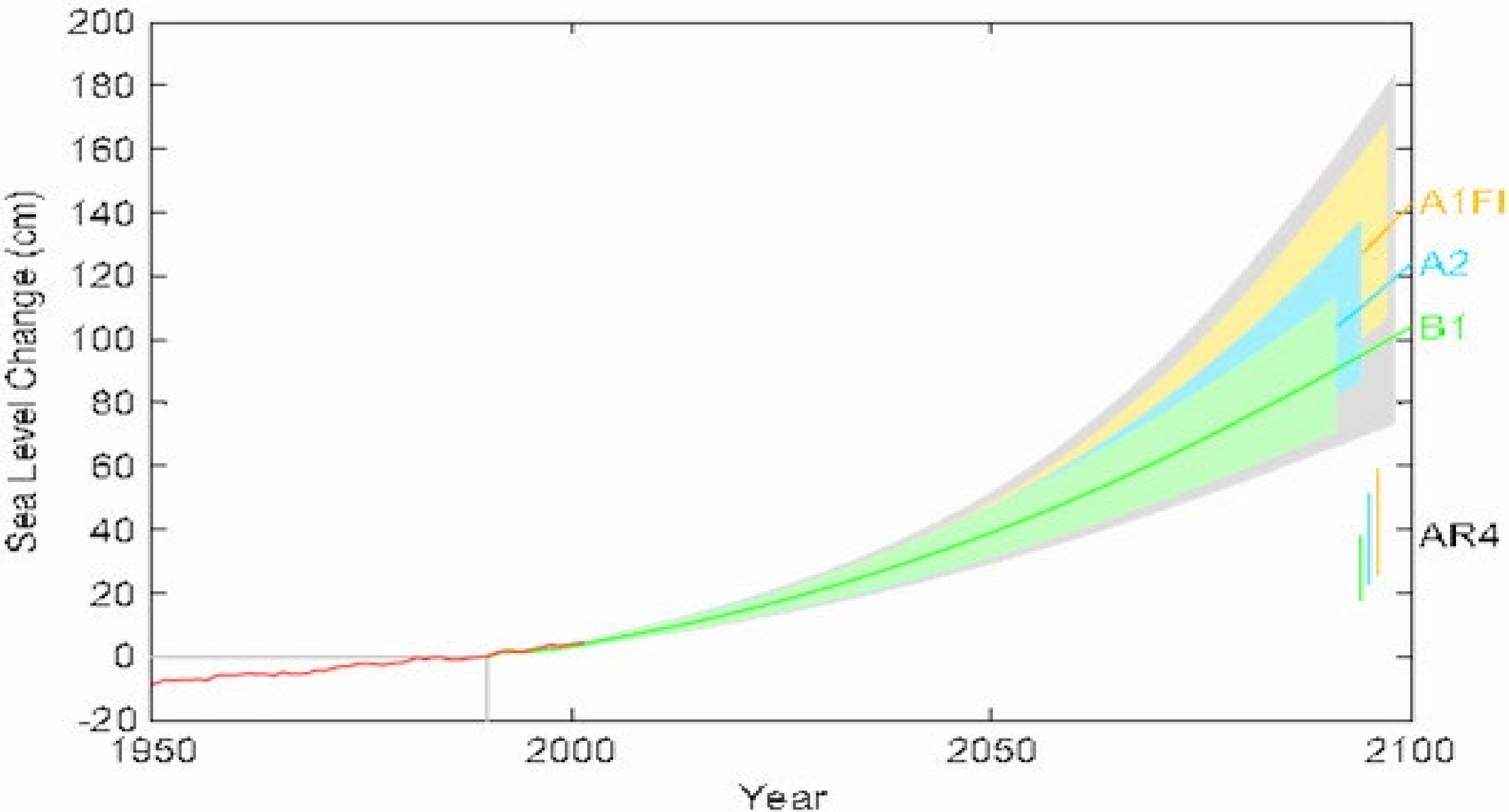



*Observed rate of sea-level rise (red) compared with reconstructed sea level calculated from global temperature (dark blue with light blue uncertainty range). Grey line is reconstructed sea level from an earlier, simpler relationship between sea level and temperature ([Vermeer 2009])*

# An early study by Levermann *et al*. 2013 found sea level rise to be roughly linear with final temperature rise

- …of 2.3 meters of sea level rise for every +1C of temperature rise.
- Since +2C is inevitable as of 2016, that's **4.6m = 15 ft of sea level rise** we're committed to.
- However, this study used only highly simplified ice dynamics models. Newer data from more comprehensive paleo studies (**Foster & Rohling 2013** ), in following slides here, indicates much stronger sea level rise

**Neither the IPCC AR5 (2013) nor AR4 modelling of glaciers included melt water on lubricating the glacier/base interface. When real-world data is used to estimate this effect… sea level rise is much worse, and clearly is still accelerating in year 2100 (Vermeer and Rahmstorff 2009). And (2013). New amplifying feedbacks (ice albedo drop, Antarctic breakup) show that even the graph below is also too optimistic. IPCC scientists themselves recognize how understated the IPCC AR4 projections are, yet they still find their way into media that wants to put a complacent and happier face on the future**



# These SERDP and NRC Projections for California are Worse. Scale is Meters of Sea Level Rise

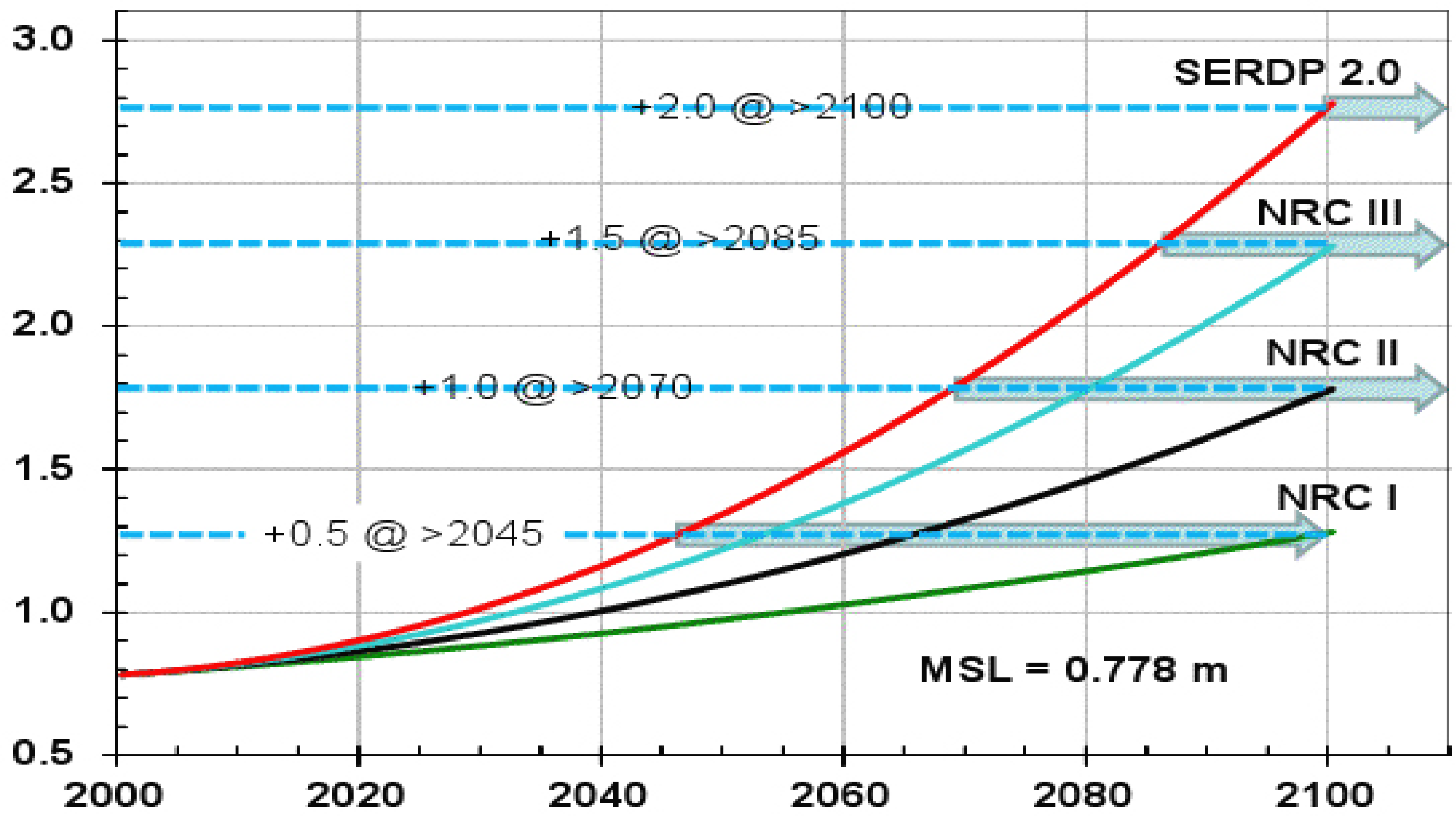



**Figure 2.** Sea level rise impact analysis benchmarks for the California coast prescribed by the Strategic Environmental Research and Development Program (SERDP) and the National Research Council (NRC). Many estimates project that mean sea level in California will increase 0.5 to 1.4 meters over 2000 mean sea level by 2100.

# Eventually, from Raymo *et al.* 2012

- (from the paper's Abstract) - "*… observations of Pleistocene shoreline features on the tectonically stable islands of Bermuda and the Bahamas have suggested that sea level about 400,000 years ago was more than 20 meters higher than it is today. Geochronologic and geomorphic evidence indicates that these features formed during interglacial marine isotope stage (MIS) 11, an unusually long interval of warmth during the Ice Ages* (similar to today's temps)
- *"Here we show that the elevations of these features are corrected downwards by 10 meters when we account for post-glacial crustal subsidence of these sites over the course of the anomalously long interglacial. On the basis of this correction, we estimate that eustatic sea level rose to **6–13m** above the present-day value in the second half of MIS 11.*

# That’s 20-40 feet of sea level rise

- *This suggests that both the Greenland Ice Sheet and the West Antarctic Ice Sheet (WAIS) collapsed during the protracted warm period while changes in the volume of the East Antarctic Ice Sheet were relatively minor, thereby resolving the long-standing controversy over the stability of the East Antarctic Ice Sheet during MIS 11.”*
- *(new in 2014 – confirmation that WAIS is now already in irreversible collapse)*
- Given the permanence of the climate change we are causing, it is likely that a similar collapse of the Greenland and East Antarctic ice sheets is also in our future, even with gradual conversion to renewable energy sources.

# Raymo *et al.* find even today's temperatures lead, longer term, to large sea level rise

- During interglacial period MIS 11, $O^{18}/O^{16}$ temperature proxy data shows global temperatures were ~identical to today's (**source; p 457**).
- Therefore: allowing temperatures to remain at today's levels may lead to not just the loss of all permanent Arctic Ocean sea ice (a process which is now at most only a ~decade away) but to the melting of all of the northern hemisphere polar ice, thence to the large sea level rises seen by Raymo *et al.* in MIS 11.
- But as we just saw, even halting ALL anthropogenic carbon emissions on Earth, still **will not lead to temperature reductions.**
- Here's another source on future sea level rise…

# This video packs a lot of ice-sheet/ sea level rise science into 6 minutes

- Worth watching, part of the **Yale Climate Series**
- Still, it's ancient history: done in 2013
- Since then, we've had years of steeply rising global GHG's and temperatures, and the confirmation of the irreversible loss of the West Antarctic Ice Sheet
- And more political foot-dragging and finger-pointing, and economic growth accelerating our CO2 emissions, giving atmospheric concentrations now above 420 ppm.

**Milankovitch insolation (middle graph) predicts stable Northern Hemisphere (NH) ice volume (dotted) if we rapidly return to pre-industrial 280 ppm CO2. But if instead we continue raising CO2 to ~double present values, all NH ice disappears (dashed curve bottom graph) until Milankovitch cooling begins again about 20,000 years from now. source, p. 459**

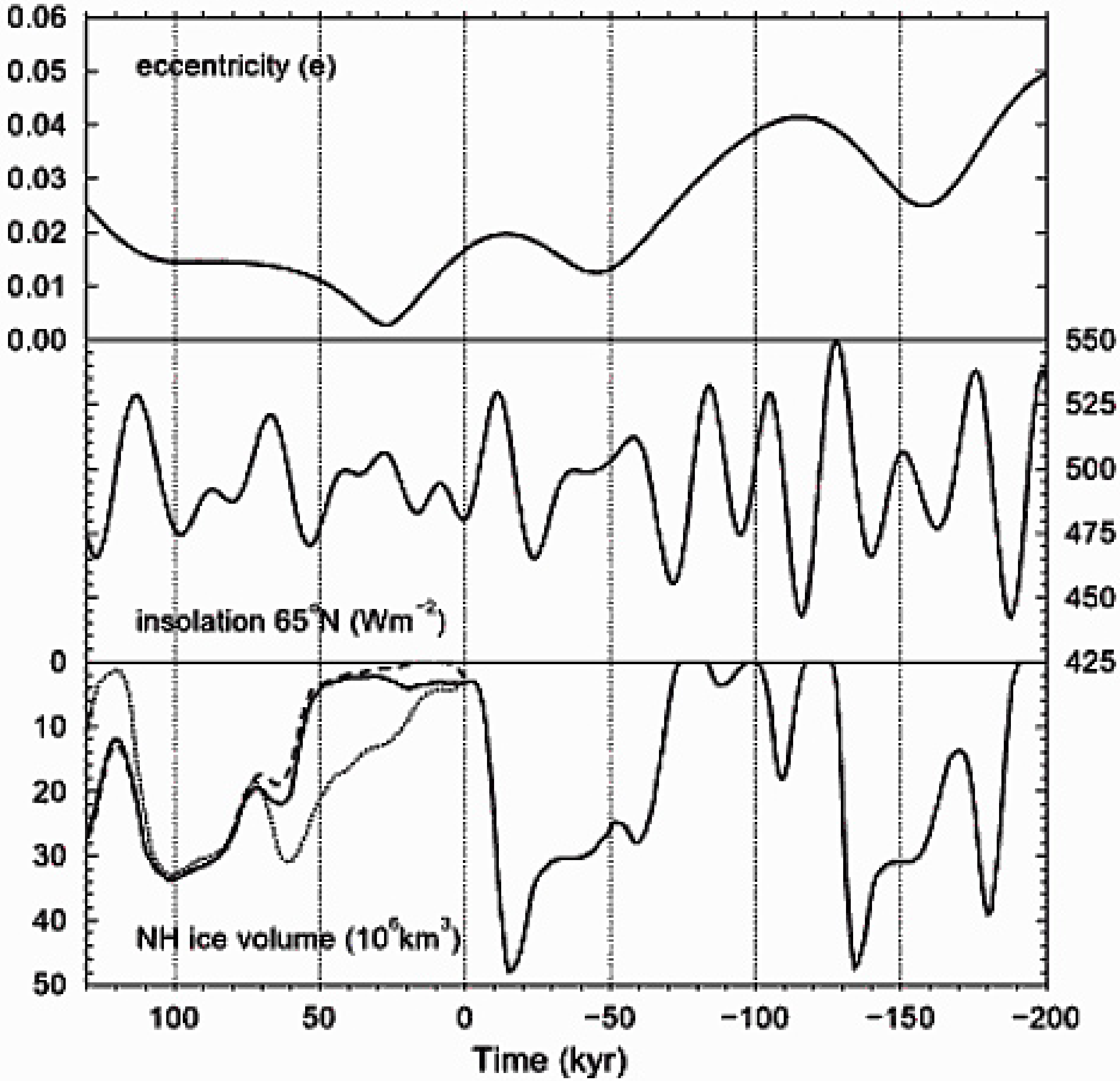
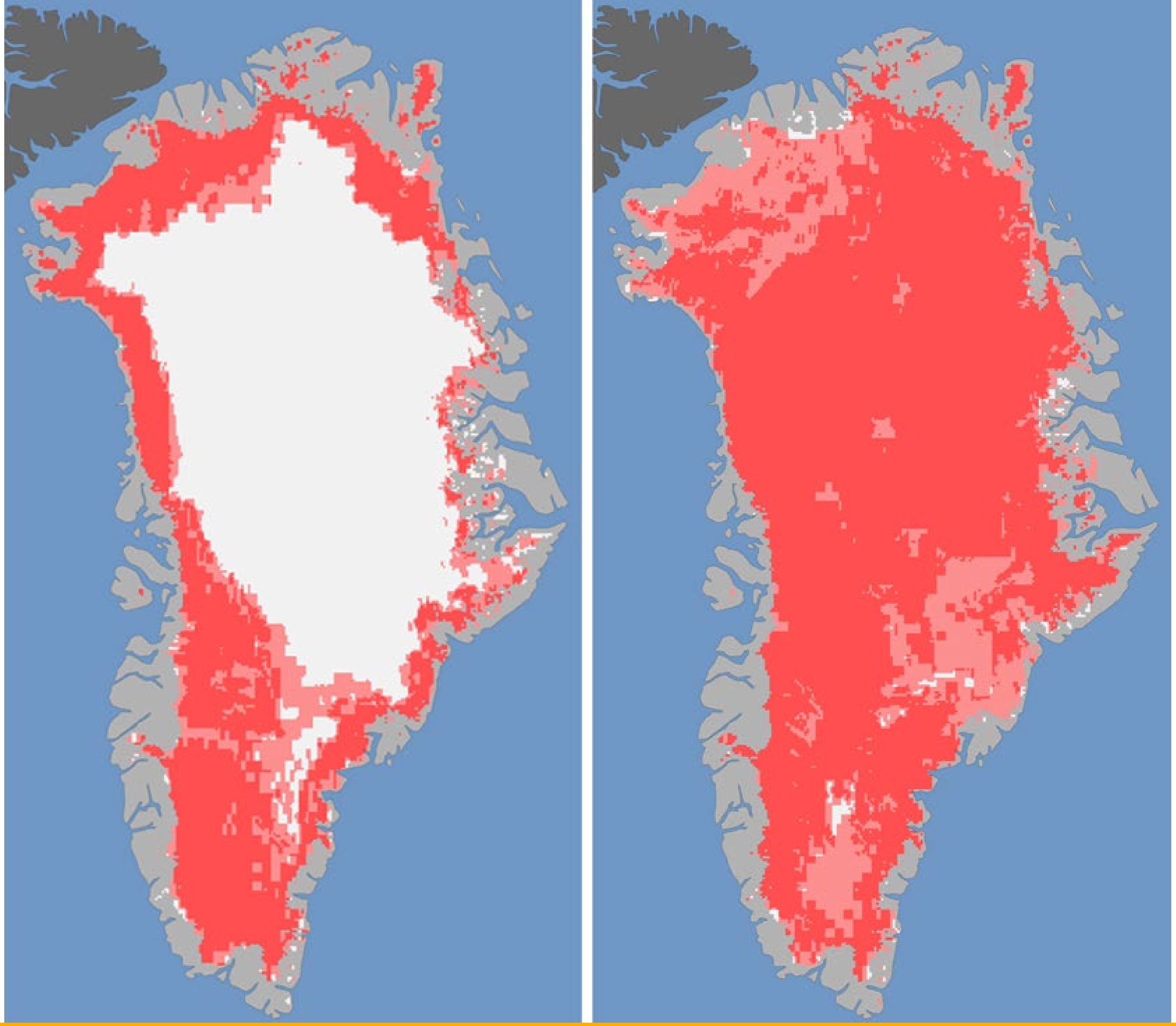



**FIGURE 15.16** Long-term variations over the period from 200 ka BP to 130 ka AP of eccentricity (e), June insolation at 65°N (Wm$^{-2}$) (Berger, 1978), and NH ice volume ($10^6$ km$^3$) (Berger and Loutre, 2002). In the panel Ice Volume: the solid line is the ice volume simulated by using the Vostok $CO_2$ concentration for the past (Petit et al., 1999) and a scenario reproducing the last 120 ka for the future; the dotted line gives the future ice volume if the future $CO_2$ would remain constant and equal to 210 ppmv; the dashed line is for the future ice volume under a scenario where the $CO_2$ concentration would reach 750 ppmv within the next two centuries and return to the 'natural Vostok level' 1000 years later.



In 2012 for the first time on record, Greenland had surface melting across its entire surface, even the coldest, highest altitude inland locations. Partially melted ice is less reflective, inducing further melting. Increasing wildfires are adding dark soot and ash to surface snow as well, especially in 2012. See Box *et al.* 2012 for the declining albedo of the Greenland ice cap. If/when Greenland melts entirely, it will contribute 23 feet to global sea level.

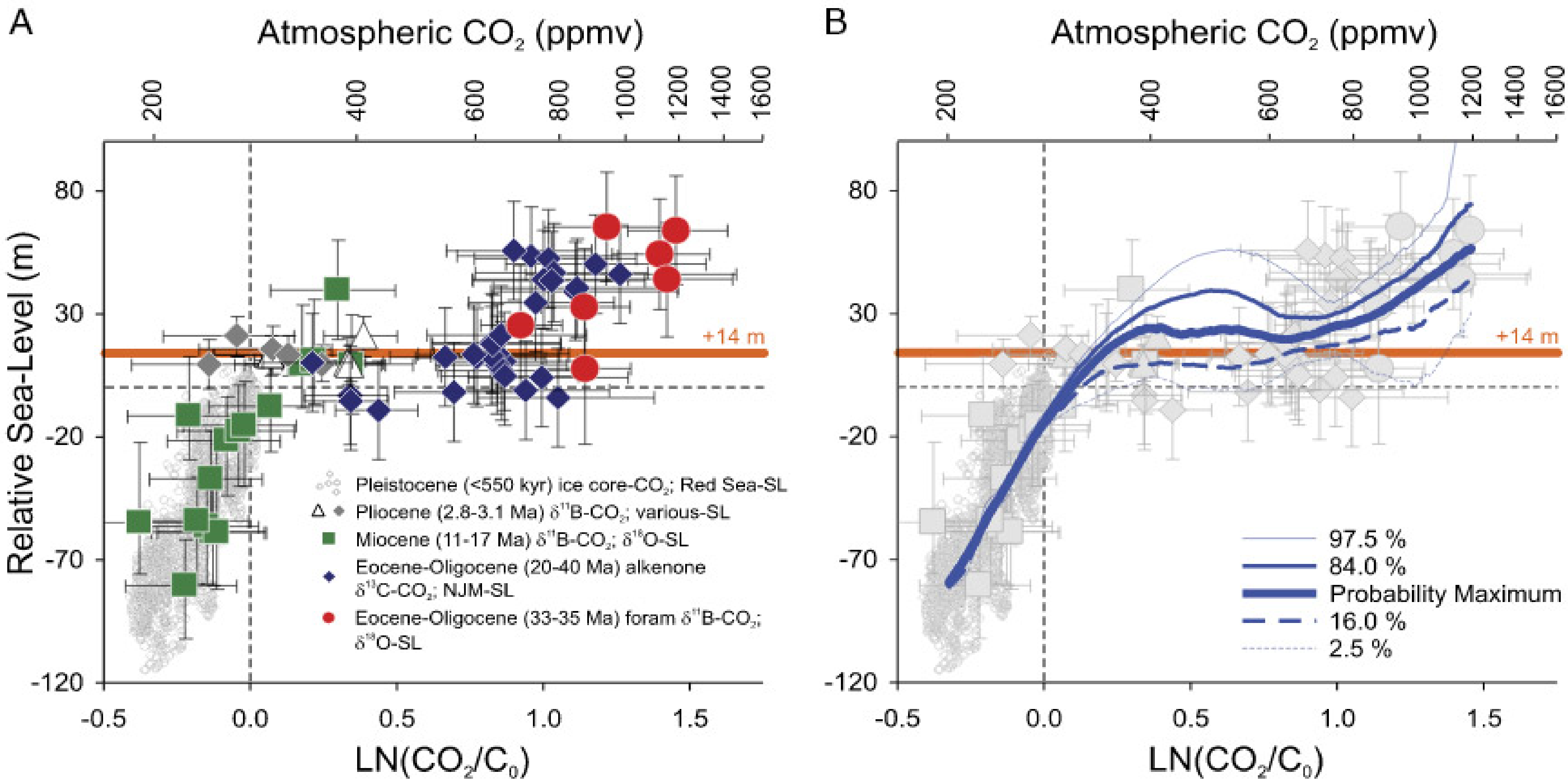
# Newer studies show sea level rise will actually be far worse

- **Raymo *et al.* studied just one location - the Bahamas - to get these sobering 20-40 ft sea level rise levels.**
- A year later, Foster and Rohling (2013) published a work consolidating evidence from the past ~40 million years at many locations to determine sea level rise at thermal equilibrium (when climate has finally stabilized at a given new CO2 level) for various CO2 levels.
- **They find that at CO2 of 400 ppm (20ppm lower than today's level), sea level will rise at least 9m and most likely ~24m above present levels**, due to complete melting of Greenland, and the West Antarctic Ice Sheet (WAIS), and part of the remainder of Antarctica as well. **24m is 80 feet.**

# 80 feet of sea level rise will submerge most of our greatest cities

- …and hundreds of thousands of square miles of continental area, including the prime farmland in delta regions worldwide (and California). Geology.com shows how such rising sea levels flood key areas, including Santa Cruz County.
- Delaware was the first state to join the United States, and it will be the first to disappear underwater (bits of Florida will still remain when Delaware finally is gone).
- **First in / First out. FIFO.** That's the accounting method Nature will use to tax our inactions, it seems.
- **How will flooding prime delta soils affect our ability to feed ourselves?**

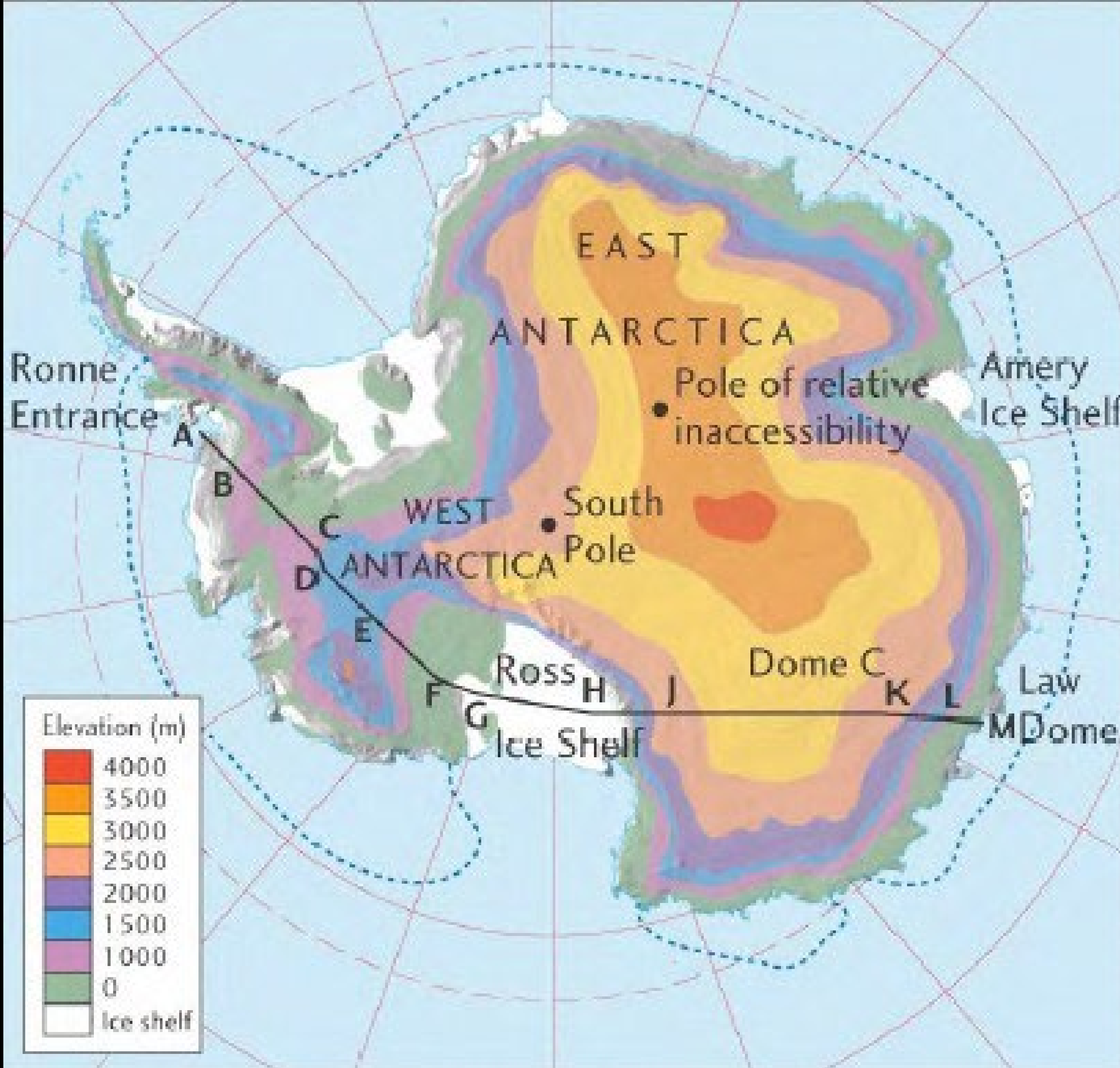
**Foster & Rohling 2013 - Paleo climate shows that 400 ppm CO2 leads to final sea level rise of ~24m (80 ft) above today's, and conclude *"Our results imply that to avoid significantly elevated sea level in the long term, atmospheric $CO_2$ should be reduced to levels similar to those of pre-industrial times."* (That's 280 ppm, *vs.* today's 420 ppm). 350.org's goal of reduction to 350ppm is not enough.**



# 6. Collapse of the Cryosphere: Ice Sheet Instability

# As of 2014: Collapse of the West Antarctic Ice Sheet (WAIS) Has Begun

- NY Times Article on new published research paper.
- Warmer waters underneath the ice shelves at the terminus of the West Antarctic glaciers has eaten away at the bottom of the ice mass, disconnecting the grounding line and begun the collapse of the ice sheet.
- It is now described as "unstoppable". Thomas Wagner, director of NASA's Polar Ice Sheets program: ***"There's nothing that can stop it now".***
- While most of the cause is the warmer waters surrounding Antarctica due to greenhouse warming, it is also being exacerbated by geothermal heating. A tectonic spreading zone underlies parts of West Antarctica (but no evidence this geothermal heating has been anything but constant over recent geologic time – Schroeder *et al.* 2014)


EAST
ANTARCTICA
Pole of relative inaccessibility
South Pole
WEST ANTARCTICA
Ronne Entrance
Amery Ice Shelf
Ross Ice Shelf
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D
E
F
G
H
J
K
L
M
Elevation (m)
4000
3500
3000
2500
2000
1500
1000
0
Ice shelf

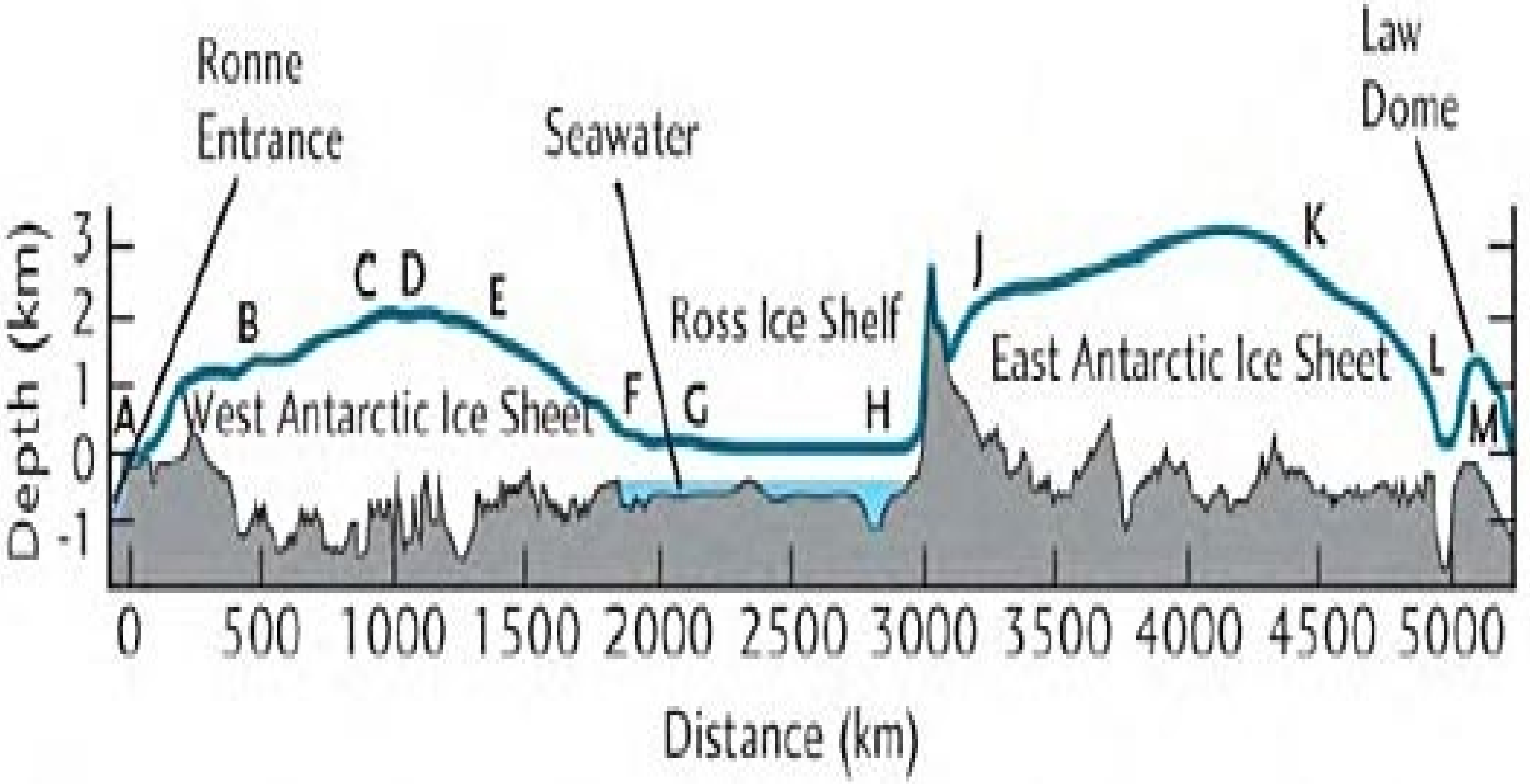
# The West Antarctic Ice Sheet (WAIS) sits in a shallow ocean basin

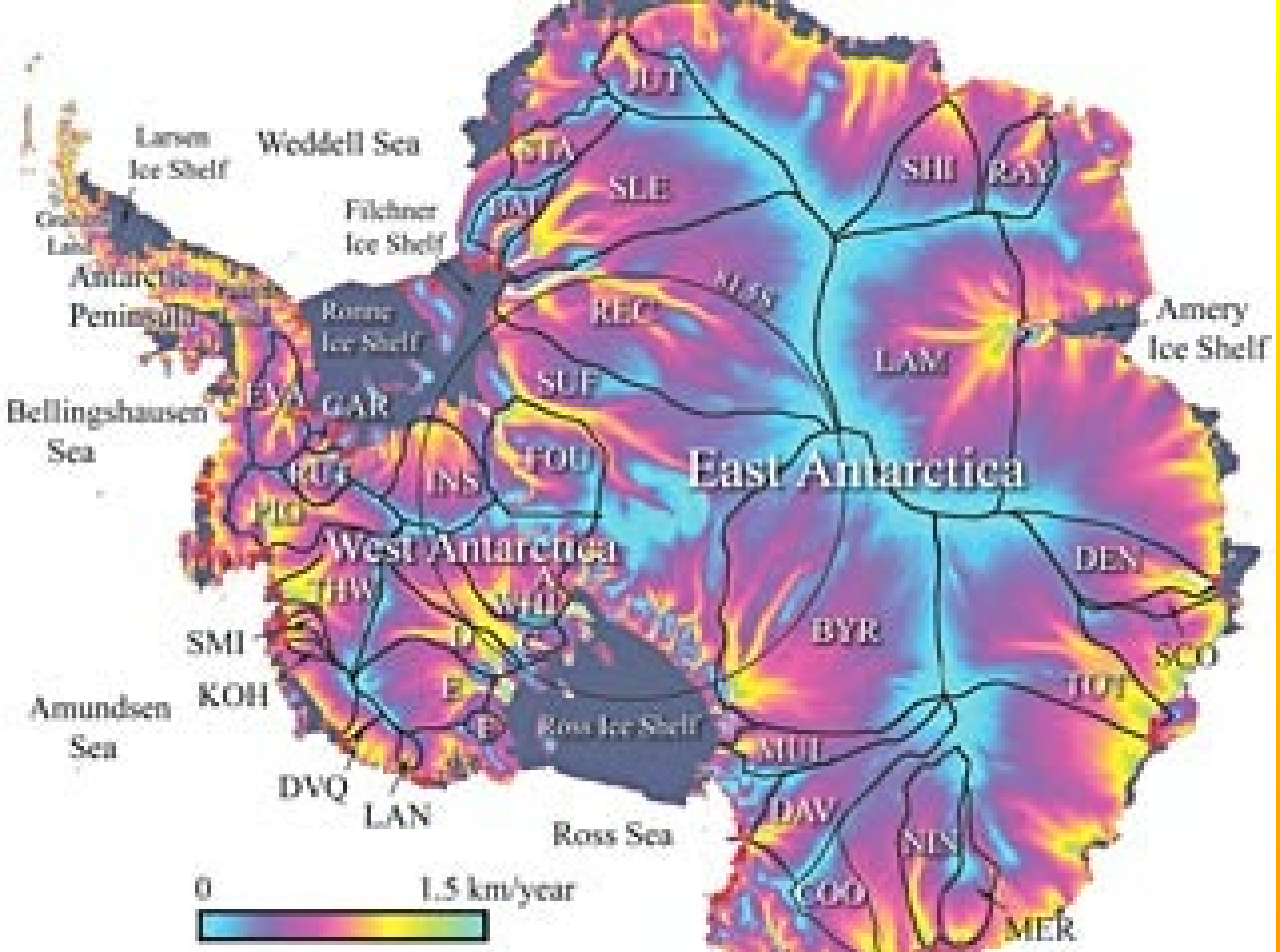
- The West Antarctic Ice Sheet is grounded in a shallow ocean basin, which it fills. If that ice melts enough to pull the bottom of the ice off the sea floor ridges, it is no longer anchored, can no longer resist being pushed by the attached landed glacial ice sheets experiencing gravity, and they accelerate and slide into the warmer ocean.
- This is now happening (**Rignot *et al.* 2014**)
- This process was **predicted back in 1978 by glaciologist John Mercer**
- **From this alone, global sea level rise will almost certainly go up ~5m going forward**, the timing depends on our actions. And more in the Northern Hemisphere, due to gravity effects.

# New in 2017: West Antarctic Collapse Much Faster than Old Climate Models

- Glaciologists had puzzled over why their climate models failed to hind-cast the strong sea level rise during the Pliocene, at temperatures very similar to today.
- The new work on West Antarctica, and the discovery by Richard Alley that marine-terminating glaciers cannot support cliffs higher than 300 ft without collapse, help resolve this.
- They now predict the West Antarctic collapse could happen over decades, not centuries, and predict 6+ ft of global sea level rise (more, in the U.S.) by 2100 on our current path (for the layman, **here**)

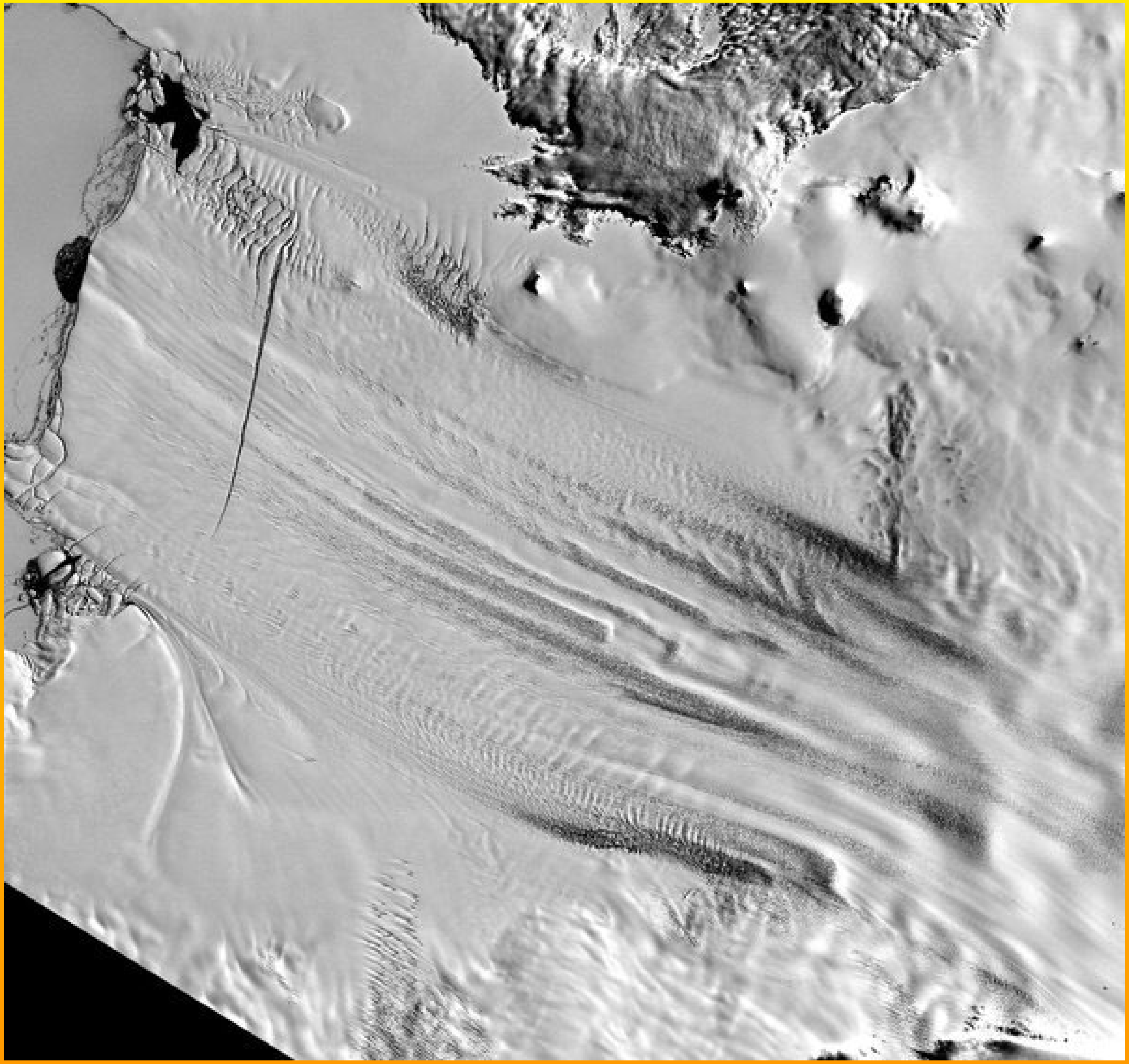
# Antarctica's ice sheets elevation profile: Note WAIS sits on a shallow ocean basin, grounded until now by the ridge lines under the Ross Ice Shelf





Larsen Ice Shelf
Weddell Sea
Filchner Ice Shelf
Antarctic Peninsula
Ronne Ice Shelf
Bellingshausen Sea
JUT
SLE
SHI
RAY
REC
LAM
Amery Ice Shelf
SUP
EVA
GAR
FOU
INS
East Antarctica
West Antarctica
THW
DEN
BYR
SMI
KOH
SCO
Amundsen Sea
Ross Ice Shelf
MUL
DVQ
LAN
DAV
Ross Sea
NIN
MER
0
1.5 km/year

# Satellite photo: Breakup of the West Antarctic Ice Sheet Has Begun (reported May '14). Thwaites Glacier Terminus is below



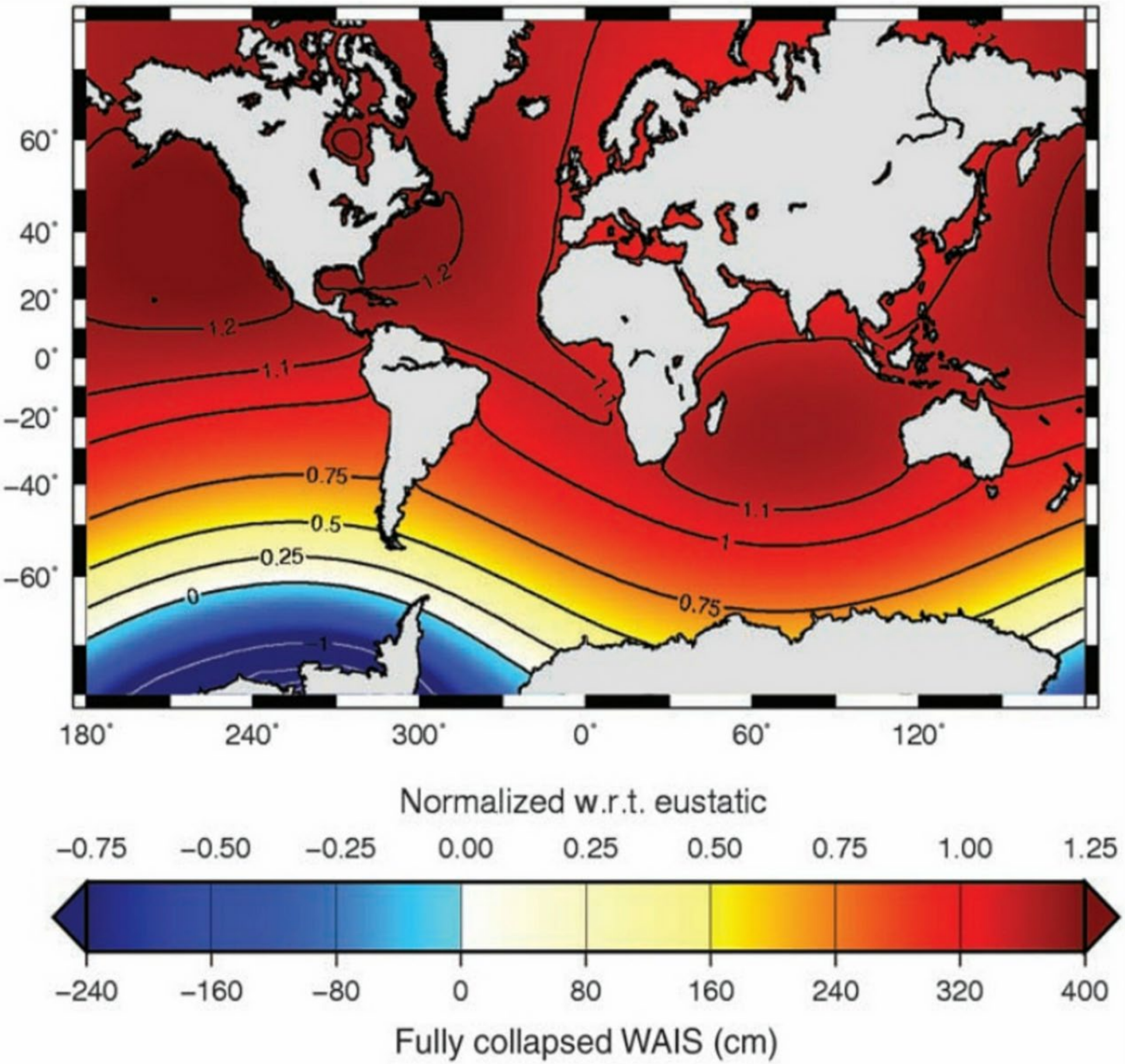
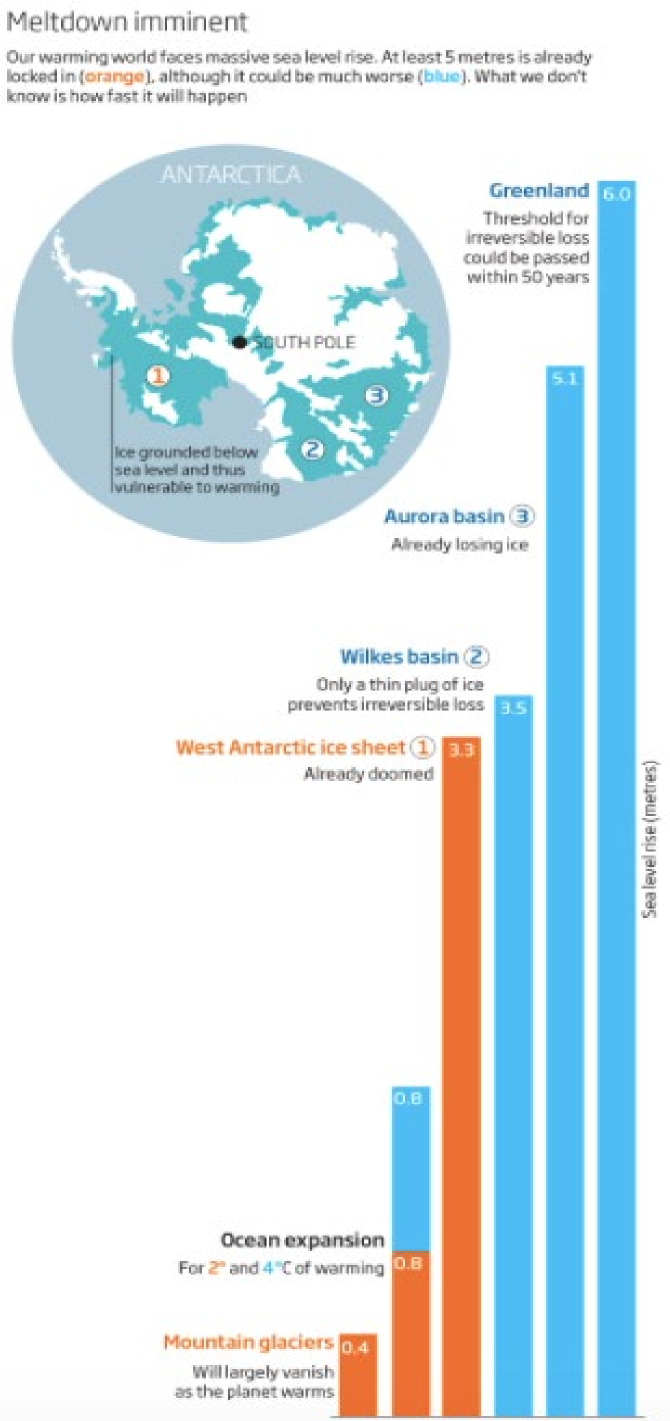



**Fig. 3.** Regional SLR after instantaneous removal of ice from the ROI, including the effects of self-gravitation, elastic rebound of the lithosphere, and Earth rotation perturbations but excluding the effects of ocean circulation (*29*) and other sources of ocean mass. w.r.t., with respect to.

**The gravitational attraction of the oceans towards Antarctic Ice will lessen as it melts, preferentially raising sea levels in the NORTHERN hemisphere. Worst hit is North America**




Bars show how many meters of global sea level rise to expect from different sources. Ice sources in orange were already doomed as of this 2014 graph.

# New Study: Greenland/Antarctic Tipping Point is here

- **Pattyn *et al*. (2018)** and discussed **here** finds that the tipping points for both the Antarctic (mostly West Antarctic) and Greenland ice sheets is between +1.5C and +2C. We just spent all of 2023 above 1.5C.
- These temperatures are unavoidable at this point. There's too much existing climate forcing so the equilibrium delta in temperatures is only rising, not falling

# UN Political Pressure on the IPCC Scientists Led To…

- …creating ice melt scenarios that most scientists argue are both **unrealistic** and now, **futile (2018)**…
- *"Many models of the 1.5-2C scenario allow for this threshold to be breached in the short term, potentially heating the planet several degrees higher, before using carbon capture and other technologies to bring temperatures back into line by 2100."*
- *"The study warned against this approach, however, saying that a feedback loop set off by higher temperatures would* ***'lead to self-sustained melting of the entire ice sheet' even if those rises were later offset."*** (hysteresis; it can be harsh)

# Realty Information Company Zillow Calculated U.S. Home Value Losses for merely a 6 ft Sea Level Rise

- They find it would total a **thousand Billion dollars**. That's $1 Trillion, for a mere 6 ft sea level rise.
- That only includes home values, not the larger infrastructure losses, loss of life (these floodings will happen during storms at first, before settling into permanence) and all the rest which go with this.
- And that trillion dollars is only for the U.S. For the world, obviously far higher.

# 7. Ocean Acidification

# How $CO_2$ alters the Acid/alkaline Ocean Balance

- Higher $CO_2$ pressure in the atmosphere diffuses into the ocean.
- $CO_2$ plus $H_2O$ gives carbonic acid $H_2CO_3$
- This alters the carbonate balance, crippling the ability of sea life to make their exoskeletons of calcium carbonate
- The **aragonite** form of calcium carbonate is especially sensitive – the basis for much phytoplankton, corals, and most (but not all) sea life calcium carbonate

# 21st Century Ocean Acidification

- Even using the overly conservative **2007 IPCC AR4** scenarios, by the year 2050 the oceans will be too acidic for the survival of coral reefs, and they will disappear
- Coral reefs to dissolve when CO2 doubles from pre-industrial levels (**Silverman *et al.* 2009**). It's already begun.
- At higher levels, the key parts of the entire **food web of the ocean is endangered**, as many species of microbes, plants, and animals use aragonite calcium carbonate exoskeletons which dissolve in too-acidic oceans
- **Shellfish reproductive failures** due to acidification have already arrived.
- **Loss of calcareous marine life also means significantly reduced ability to convert CO2 into CaCO3 and remove it from the biosphere for geologic time scales.**
- ***Already, primary productivity in the oceans has dropped significantly over the past century (Boyce et al. 2014)***

# In May 2014 News…

- Ocean acidification dissolving the shells of pterapods off the U.S. West Coast. These are a key species forming the base of the marine food chain.
- We'd hoped this might not start till decades later, but…
- *"The process has already begun" Below is a pterapod placed in water at ocean pH predicted for 2100. It dissolves.*

# Now in 2020, the Shells of NorCal Dungeness Crabs are Dissolving (source journal paper)

**Coral Reefs are Dying. The Great Barrier Reef: 90% has been bleached, 35% of the central and northern reef is dead, as of mid 2016.** See **"Chasing Coral"** on Netflix

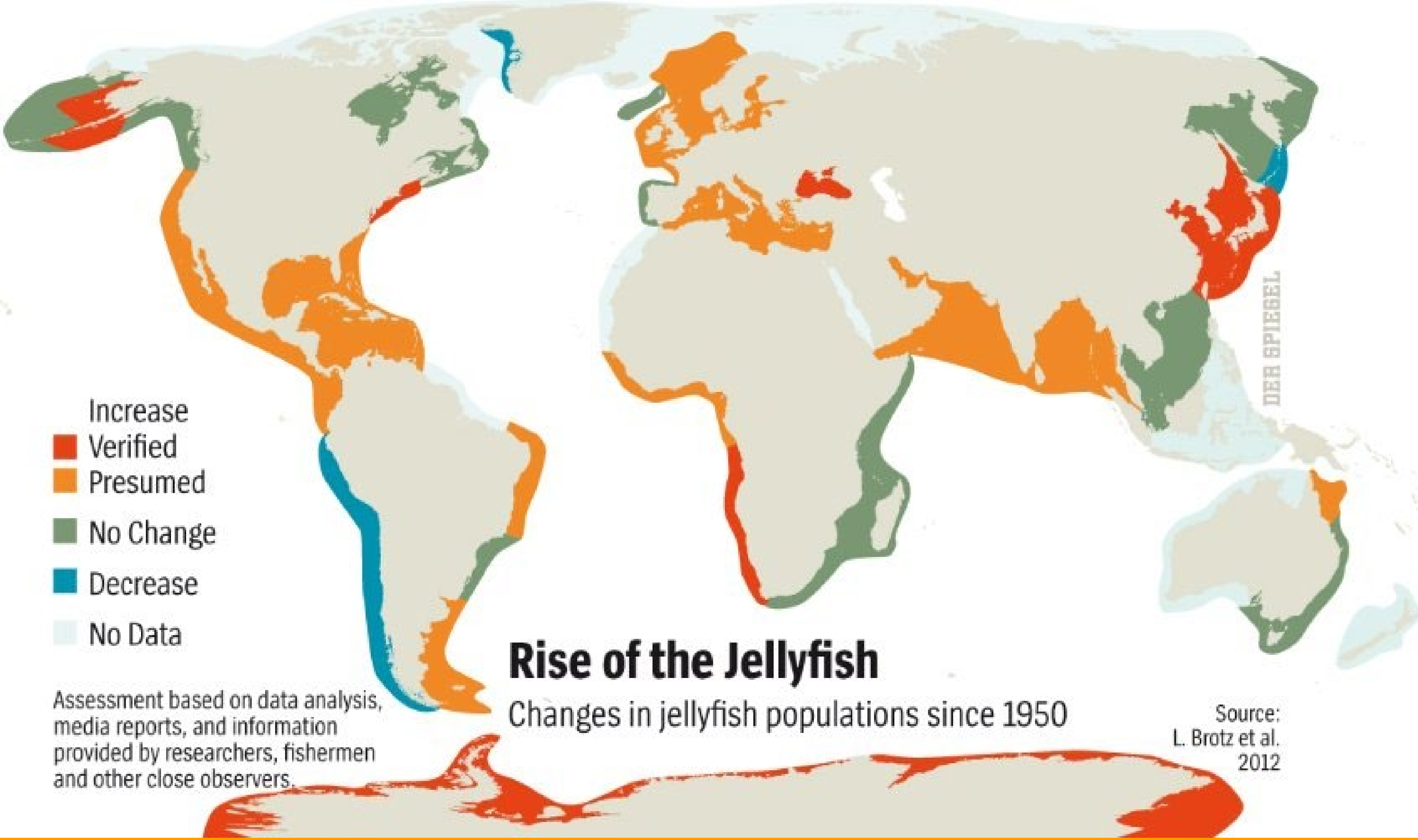
# As ocean phytoplankton and other aragonite species perish…

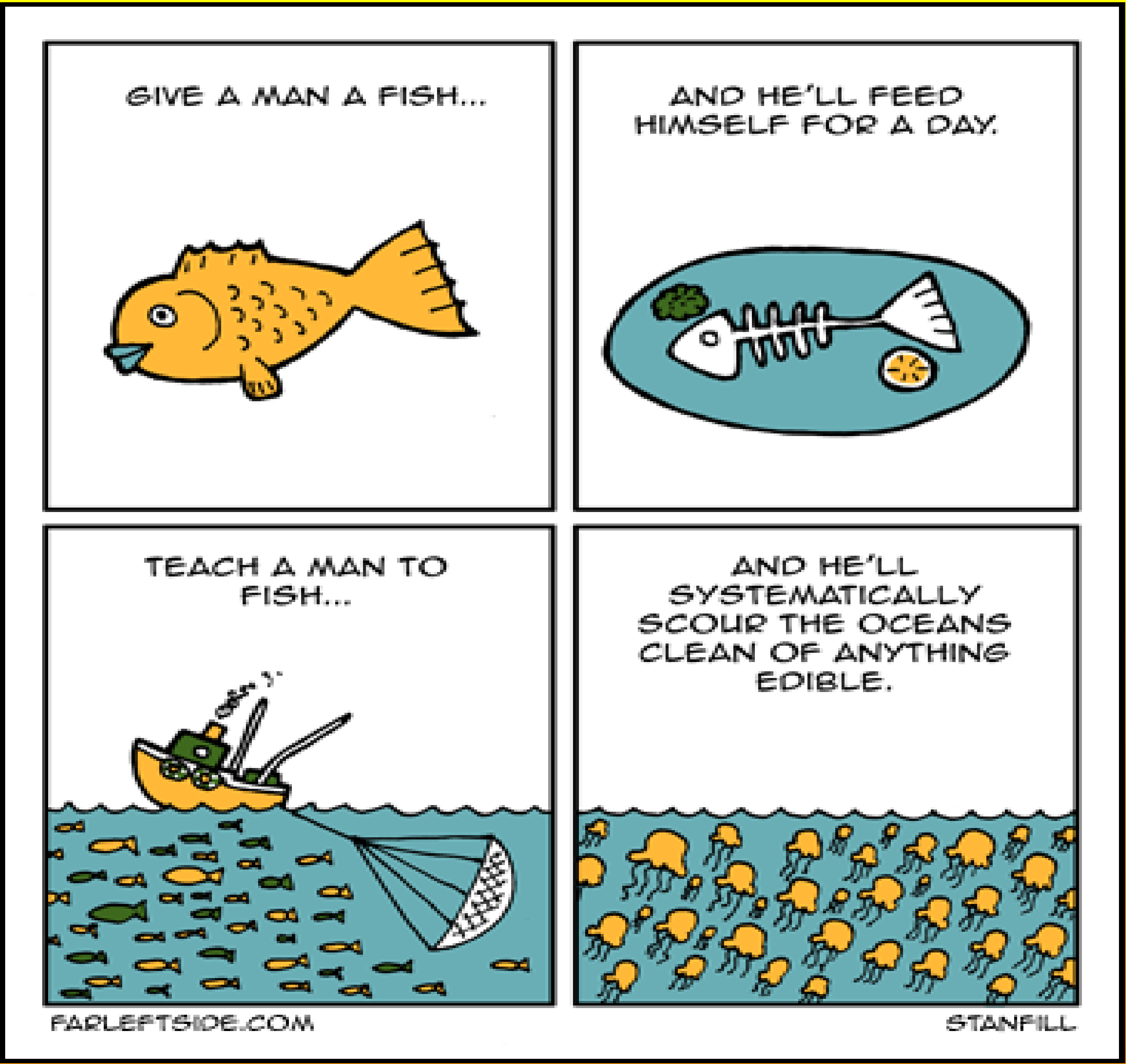
- …in hot, acidifying oceans, they will not be able to chemically convert dissolved CO2 into stable calcium carbonate, and on land - soil microbes will suffer in the droughts and heat waves to come, further crippling carbon capture in land plants and soil.
- **This is important – the ocean and land carbon sinks are in rapid decline. This is at least as important as any human emissions numbers: recall, half of our annual carbon emissions were captured by the ocean, soil, and terrestrial plants .**
- Whereas currently, with temperatures still only just above +1.2C globally, rising CO2 has been a fertilizer for plants and increasing their carbon uptake. This **"CO2 fertilization effect"** has already been crippled by 48%.

# There's efforts to undertake <u>"Assisted Evolution"</u>

- … to breed tougher corals that can withstand the heat of the future ocean.
- There's been some small successes, but the prospect of trying to replace the vast ocean areas of coral with new tougher corals before those areas are overtaken by other non-coral species, is a steep uphill enterprise.

# The Rise of the Jellyfish




GIVE A MAN A FISH...
AND HE'LL FEED HIMSELF FOR A DAY.
TEACH A MAN TO FISH...
AND HE'LL SYSTEMATICALLY SCOUR THE OCEANS CLEAN OF ANYTHING EDIBLE.
FARLEFTSIDE.COM
STANFILL

# Why the Loss of Phytoplankton and Rise of the Jellies?

- The many possible reasons are not well quantified yet, but it's clear the main causes are man-made….
- **1.** Ocean acidification and resulting destruction of carbonate exoskeletons
- **2.** Massive over-fishing has removed predators for jellies. Jellies are coming to dominate the oceans, and jellies eat anything, including phytoplankton
- **3.** Global warming: Hot atmosphere heats ocean from above, causing increased stratification, stronger thermocline and inhibition of upwelling of nutrients to sunlit surface waters where phytoplankton live.
- **4.** Fossil fuel burning is reducing the oxygen content of the atmosphere and oceans, preferentially favoring jellies over fish

# The process has begun. This is a 2015 image from Puget Sound, Washington

# So what can you do with Stinging Jellies?

- Not a lot. Some are trying to **make diapers and tampons out of them**.
- (I would guess there will be marketing challenges as well).
- Even infants may have to grit their teeth to deal with the future.

# 8. Weather Intensity Changes

- **Warmer Sea Surface Temperatures Mean…**
- --- more evaporation
- --- stronger vertical air temperature gradient driving stronger convection
- This drives stronger storms
- **Warmer Air Temperatures Mean…**
- --- Air can hold more water vapor, so rain is less frequent. Droughts over land…
- 7% higher saturation humidity per 1 degree C of temperature rise, predicted by the Clausius-Clapeyron equation, and confirmed by decades of observation (*e.g.* Held and Soden 2006).

# However, when saturation of the air does take place, the rarer resulting rains will be more forceful because of the higher amounts of water

- So, floods will be significantly more common
- And - higher air temps mean more precip falls as **rain** now instead of **snow**, which runs off rapidly rather than being stored for weeks or months as it slowly melts.
- For the mid-latitudes, we are transitioning from a time of frequent, gentle rains which allow soaking of the soil and plant roots, to a time of rarer rains on parched dry land with less healthy plants, and severe erosion caused by stronger deluges when and where rain does occur.

# Extreme precip events were expected to increase at the same rate: 7% per degree Celsius, just like water vapor

- This was the conclusion of **Pall *et al.* 2006**
- But climate models post-dicted that the increase would be greater, 8.3% per degree Celsius over land areas with weather stations since 1901…
- In fact, though… actual observations since 1901 show an even greater increase, of 10% per degree Celsius of global temperature rise (**Asadieh and Krakauer 2015**)
- ***"One of the clearest signs of climate change, over much of the world, is the increase in the fraction of the rain that falls in the heaviest events."*** – climate scientist Chris Fields, **cited here**

# We are already seeing more extreme deluges than even those climate models predicted. HadEX2 (top) is a century's data, *vs.* CMIP5 climate model runs post-diction average (bottom), from Asadieh and Krakauer 2015

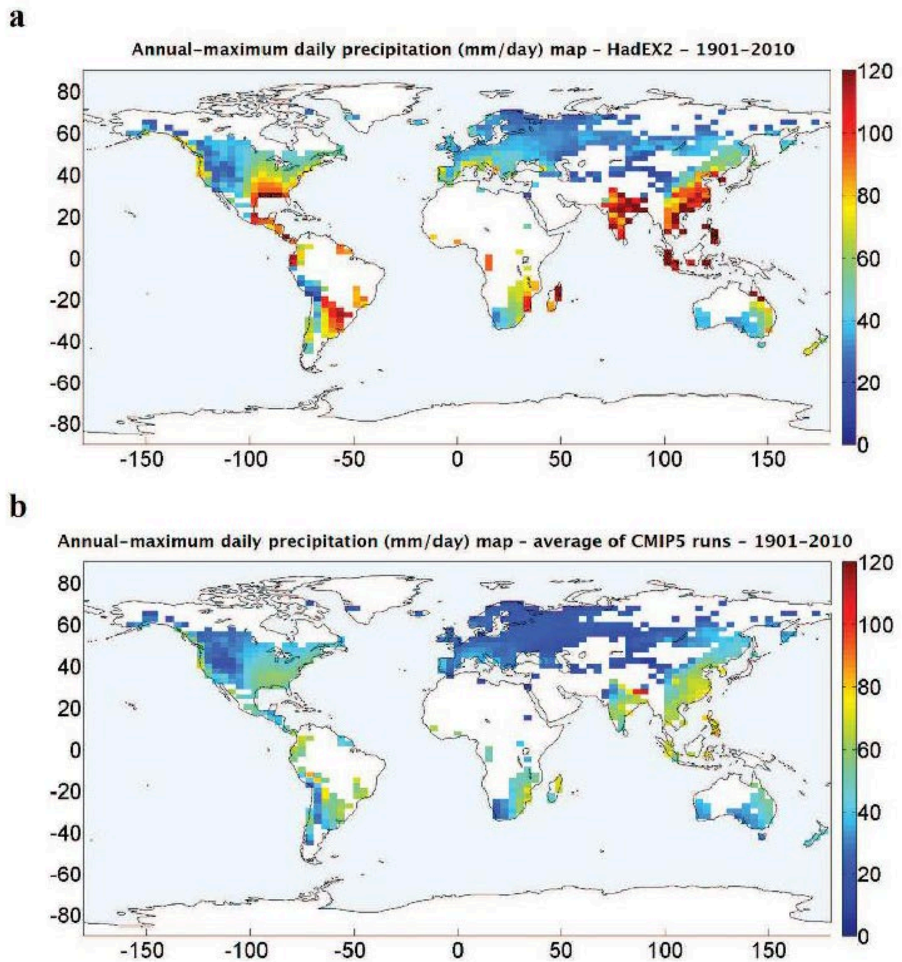
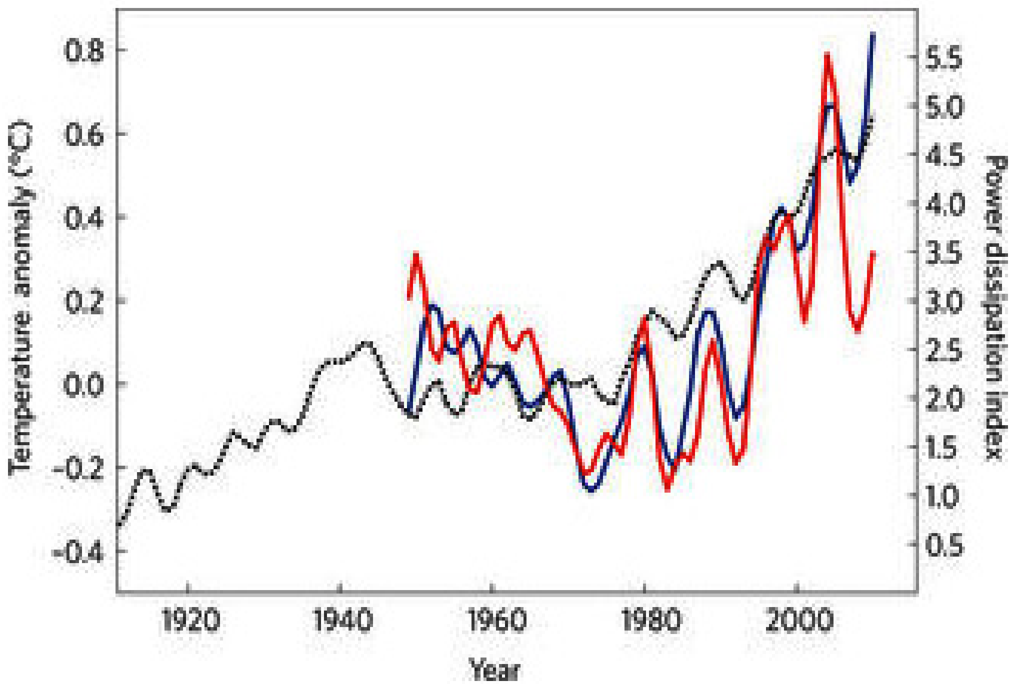



**Figure 3.** HadEX2 observational data versus CMIP5 averaged results of global extreme precipitation in 1901–2010 – annual-maximum daily precipitation map (mm $day^{-1}$) for **(a)** HadEX2 and **(b)** the average of CMIP5 model runs.

From Coumous and Rahmstorff (2012) : **Higher ocean surface temperatures go with stronger tropical storms for the future**

**Figure 3: Power dissipation index for North Atlantic tropical storms linked to tropical sea surface temperature in the main development region for Atlantic hurricanes.**



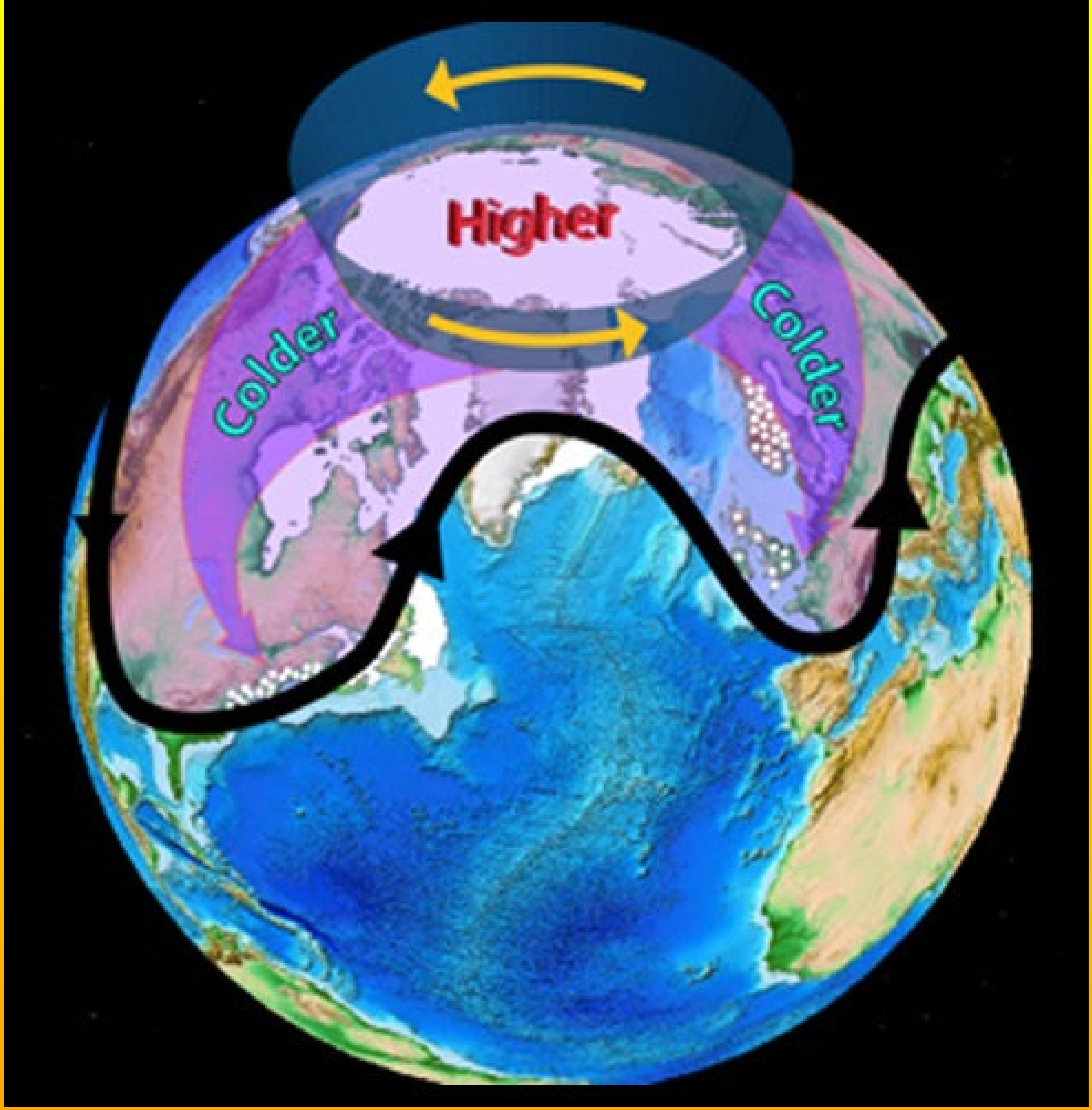

Red line denotes North Atlantic tropical storms; blue line denotes tropical Atlantic sea surface temperature. For comparison, the evolution of Northern Hemisphere mean temperature from NASA Goddard Institute for Space Studies is also shown...

# More Severe Weather in Northern Hemisphere

- Melting Arctic Ocean ice -> darker surface -> more solar radiation absorbed -> excess heat released especially in Autumn
- This heat released to the formerly cold white frozen Arctic Ocean air, warms it, weakens the cold, dense, otherwise descending air which drives the Polar Cell. The atmospheric Polar Cell ("Polar Vortex") is **breaking up into smaller pieces** which wander away from the pole (causing freakish sub-zero freezing storms such as happened in the middle and Eastern U.S. in the winter of '17/'18 and '21.
- This decreases the temperature gradient and pressure gradient across the jet stream boundary of the Polar Cell between the Arctic and middle latitudes Ferrel Cell
- The consequences are…

# Weaker Polar Cell = Meandering Polar Jet Stream

- This diminished north/south pressure gradient is linked to a weakening of the winds associated with the polar vortex (Polar cell) and polar jet stream.
- This weakened polar jet stream has larger loops in it (Rossby Waves), and it is these loops especially which cause large storms.
- The loops also are longer-lived, and as the southern ends can extend further south now, they make for more frequent slow-moving intense winter storms, and at the same time, longer and more extreme heat waves, even in the permafrost, depending on where you are in these meandering loops
- Bottom line: The larger "loops" in the polar jet stream mean **storms are more intense** and that **storms move slower**, delivering **more energy** to any given location.




Negative Arctic Oscillation conditions are associated with higher pressure in the Arctic and a weakened polar vortex (yellow arrows). A weakened jet stream (black arrows) is characterized by larger-amplitude meanders (Rossby Waves) in its trajectory and a reduction in the wave speed of those meanders.

# The Polar Jet Stream and Weather

- Dr. Jennifer Francis: A **2 hr lecture** on weather and its connection to disappearing polar ice. Good visuals in **this video (0:55 to 6:20)** interview.
- A **5:31 minute section** of this larger 2 hr lecture, which covers the **why/how of the polar jet stream and how it is changing**
- **Support:** Barnes (2013) studying 1980-2012 data, sees these patterns in the tropospheric levels, but not above the jet stream at lower pressures
- **Further support:** Arctic Ocean ice only melted through to dark blue waters beginning in year 2000, consistent with the data earlier that show no statistically significant pattern.

# A New Polar Amplifying Climate Feedback

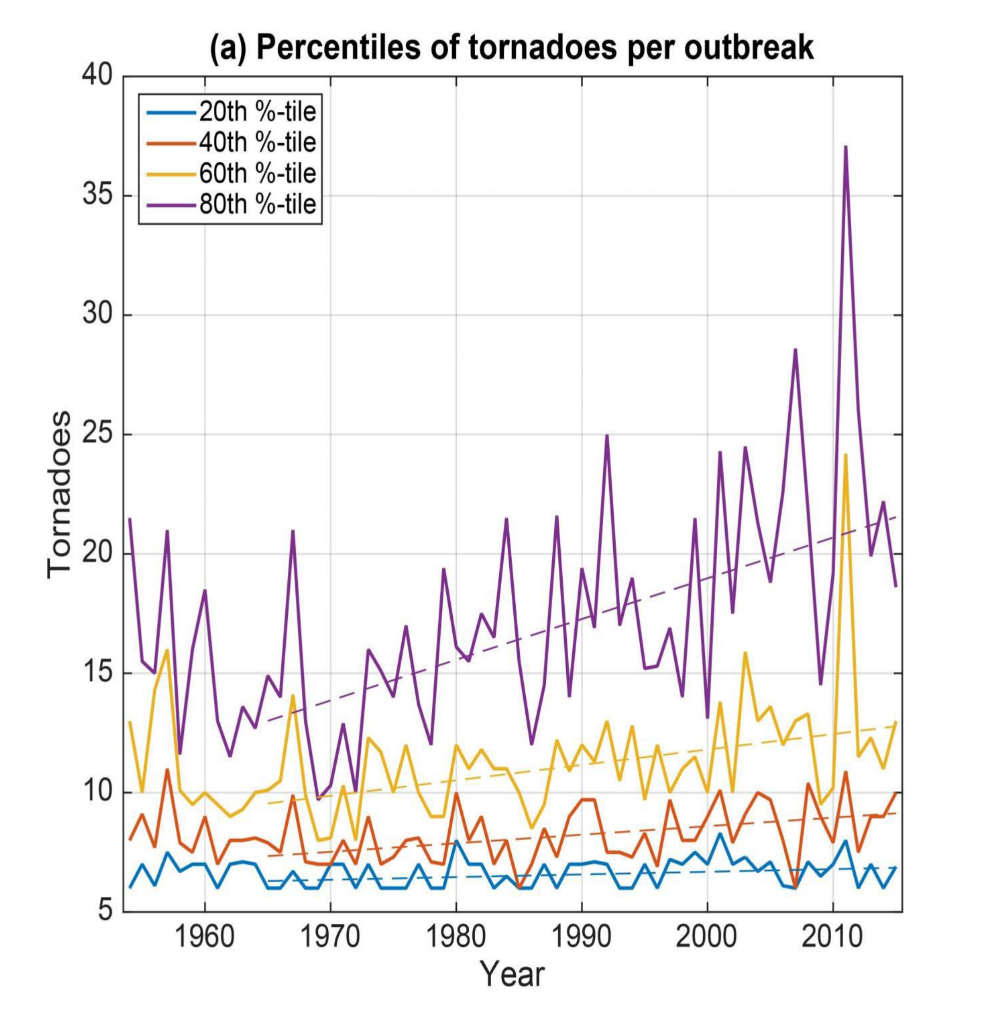
- New open water in the **Arctic Ocean (AO**) allows more solar warmth, causing evaporation off the AO, causing record high humidities, amplifying surface warming  (water vapor is a greenhouse gas too), and causing more cirrus clouds, which also trap outgoing IR and cause further warming. This strong heating is causing a more wavy polar jet stream, which further draws warm air and moisture to the AO, amplifying the entire process (**interview at AGU ’16 1:24s**)
- 2016 Fall, Winter AO temperatures were **30+ degrees Fahrenheit above normal (!)**

# When there are 5 or 7 Rossby Waves Circling the Globe…

- …the high pressure (drought) areas park right over the "breadbaskets" of the world.
- This is a new coordinated stress on civilization, as it is expected to cause food shortages globally (**Kornhuber *et al.* 2019** and **Mann *et al.* 2018**)

# What about Tornados?

# We’re seeing more tornados of all strengths, especially the strongest (Tippett and Cohen 2016, and here)




- But the details are not well understood in climate models.
- More work here is needed on what to expect for the future.
- But what we’ve seen for the past 40 years is not encouraging.

# Unlike “Clem” Schultz, you definitely should not just stand and video-record while a tornado sweeps you away

# Tornados scouring the landscape…(Wray, CO)

…have intensities which can be surprising. This may relate to superstorms - in the recent work of James Hansen and colleagues (later here)

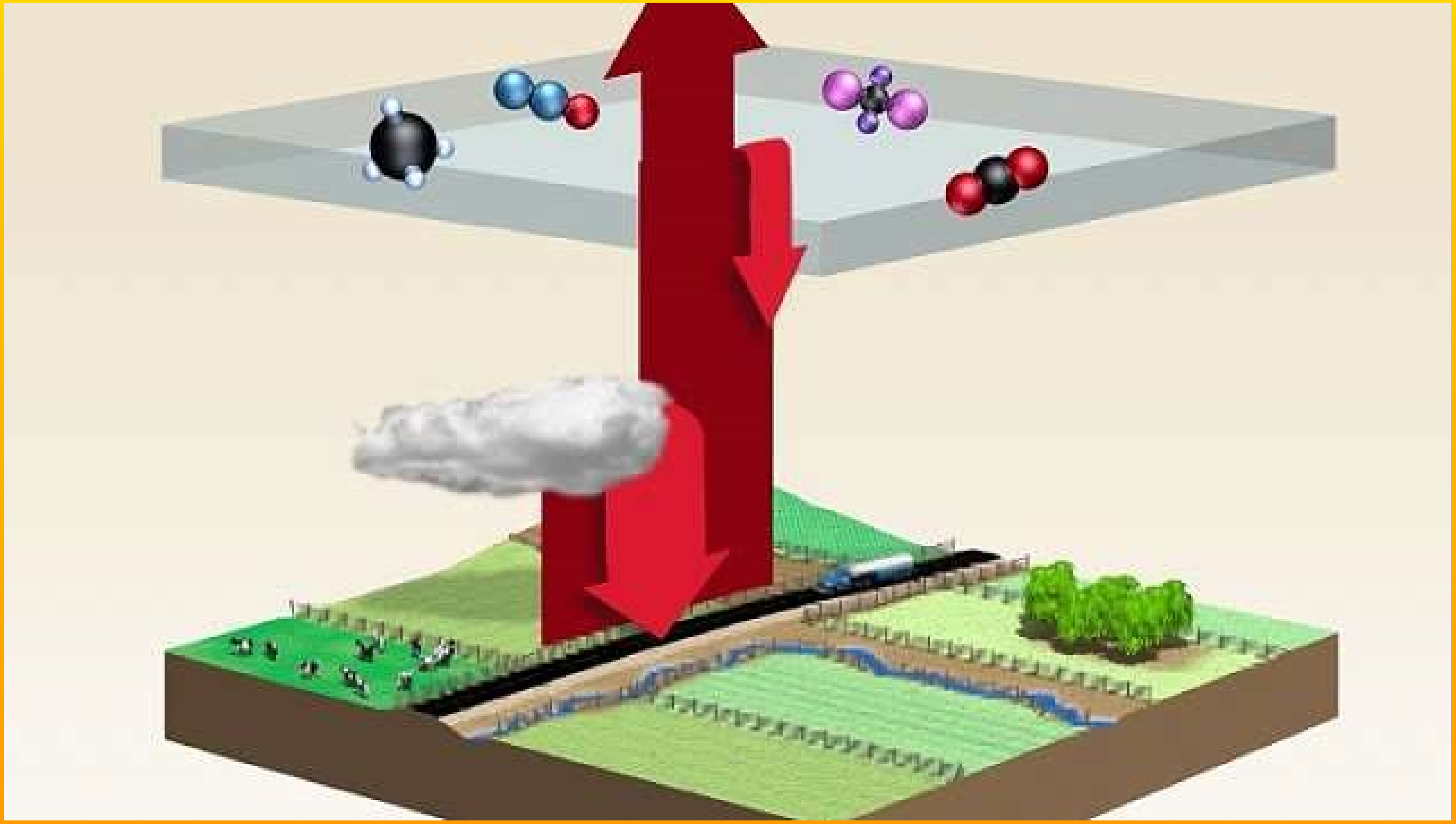
# Related: New Mechanism of Ozone Destruction Identified in a Warming World

- **Anderson *et al.* (2012)** show that more forceful summer convection, especially over the U.S., adds significant bromine and chlorine deep into the stratosphere, where it will catalyze the destruction of ozone.
- Now, **Marshall *et al.* (2020)** find strong evidence that the $2^{nd}$ of the 5 great Mass Extinctions – the Devonian – was caused by UV-induced killing of land and shallow sea plants and animals through warming-induced ozone destruction

# Warming-Driven – but how?

- Marshall *et al.* find convincing evidence there was no unusual volcanic eruptions causing massive CO2 such as implicated in other mass extinctions.
- Instead, the mechanism looks to be <u>feedback driven </u>from less dramatic initial warming…
- Destruction of ozone also means increased solar radiation from the UV can reach and warm the ground, as part of the process.

# The Ozone Destruction Feedback Loop – A New Mechanism for Climate –Induced Mass Extinctions



# From Marshall *et al.* (2020)…

- *“A positive feedback mechanism could also be at play in the Late Devonian and early Carboniferous, as there were extensive shelf seas with high volumes of **carbon** burial (2, 44) and hence high organic productivity. Methyl halogens are produced naturally by a wide range of organisms (45); hence, any increased organic productivity ultimately increased supply.”*
- *“Progressive ozone loss and increased influx of damaging UV-B would have led to the observed collapse of the Devonian forest environment together with its structured community.”*

# Dropping ozone stimulates ocean halogen producers, destroying more ozone

- Ozone killing of land forests and other biota would drain organic carbon into the oceans**, feeding organisms that produce bromine and chlorine** and other halogen compounds, now available for further convective transport up to the deep stratosphere, resulting in further ozone destruction.
- The result: an amplifying feedback leading to a **Mass Extinction**.
- This should be a serious concern for some proposed GeoEngineering carbon-offset schemes like iron spread across the open ocean, disturbing these ecological systems.

# Marshall *et al.* Concludes With…

- *“The recognition that a known extinction kill mechanism - the loss of the ozone layer - occurred not only during emplacement of a LIP”* (=enhanced volcanism, but relatively mild and localized (RN)) *“but at times of high global temperature* ***identifies a new mechanism for mass extinctions****. Recognition of the significance of bolide impacts (60) and LIPs (3) as kill mechanisms has transformed our understanding of the mass extinction process. However, unlike a LIP or a bolide impact, higher temperatures are a certainty in the immediate future with implications for a similar collapse of the ozone layer.”*

# 9. Shutdown of the Global Ocean Thermohaline Circulation:

# The AMOC Tipping Point

## Hansen *et al.* (2016) show that the advanced stages of polar melt **can shut down the global thermohaline ocean circulation**

- Greenland is melting rapidly, and too much cold fresh surface meltwater caps the warmer saltier water beneath it, and prevents it from radiative cooling, densifying, and sinking through the thermocline as it has almost always done, near Greenland in the NH and Antarctica in the SH.

# New in 2017: AMOC Shutdown Far More Likely than IPCC Had Thought

- Remember **"The Day after Tomorrow"** and the breathless comment on AMOC shutdown *"Well… I THINK IT'S HAPPENING!"*
- A new paper finds that rapid AMOC slowdown due to a convective failure of the North Atlantic SubPolar Gyre (SPG) is much more likely than **IPCC AR5** had thought, when CMIP5 models best able to reproduce actual observed stratification are examined in more detail (**Sgubin *et al.* 2017**) (***Nature* paper**)
- **Half of their most realistic models lead to AMOC shutdown and large climate change in as little as 1 decade**
- The authors **note**… ***"contrary to a potential AMOC disruption, no assessment has been made of the possibility of a local SPG convection collapse in the latest IPCC AR5 report"***

# Newer studies in 2018 add concern the AMOC may be close to the tipping point of shut down

- Studies discussed **here**, and in more detail in **RealClimate.org**, but *Nature* papers are behind a paywall.
- **Prof. Michael Mann notes the AMOC weakening is happening a full century ahead of model predictions.**
- Peter Ward (U. Washington)  warns that shutdown of the global ocean circulation due to rapid rise of volcanic CO2 is suspected or implicated in the 4 of the 5 great Mass Extinctions, when the resulting **anoxic deep oceans generated deadly hydrogen sulfide $H_2S$ which rose to the surface, into the atmosphere and killed most life on Earth (but newer climate models of $H_2S$ diffusion suggest insufficient concentration to lead to mass extinctions).**

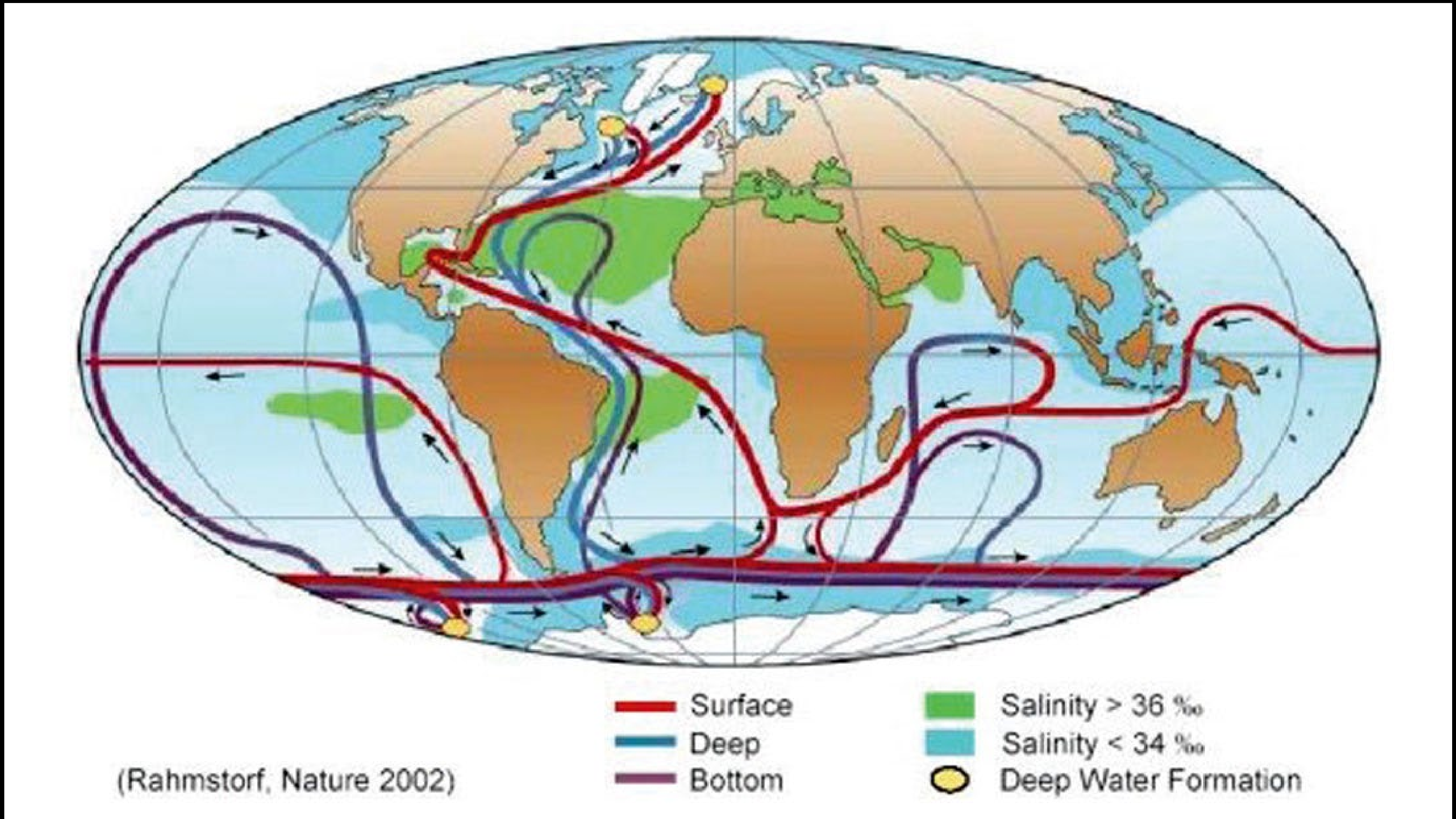
# Not just meltwater, but increasing rain in the Arctic…

- …as predicted by climate models for our 21st century, further freshens and lowers the density of surface waters inhibiting sinking through the thermocline, while strongly heating stagnant surface tropical waters, and the resulting stronger temperature pole/tropics temperature gradient drives far more intense storms.
- This happened during the **Eemian Interglacial** 120,000 years ago.

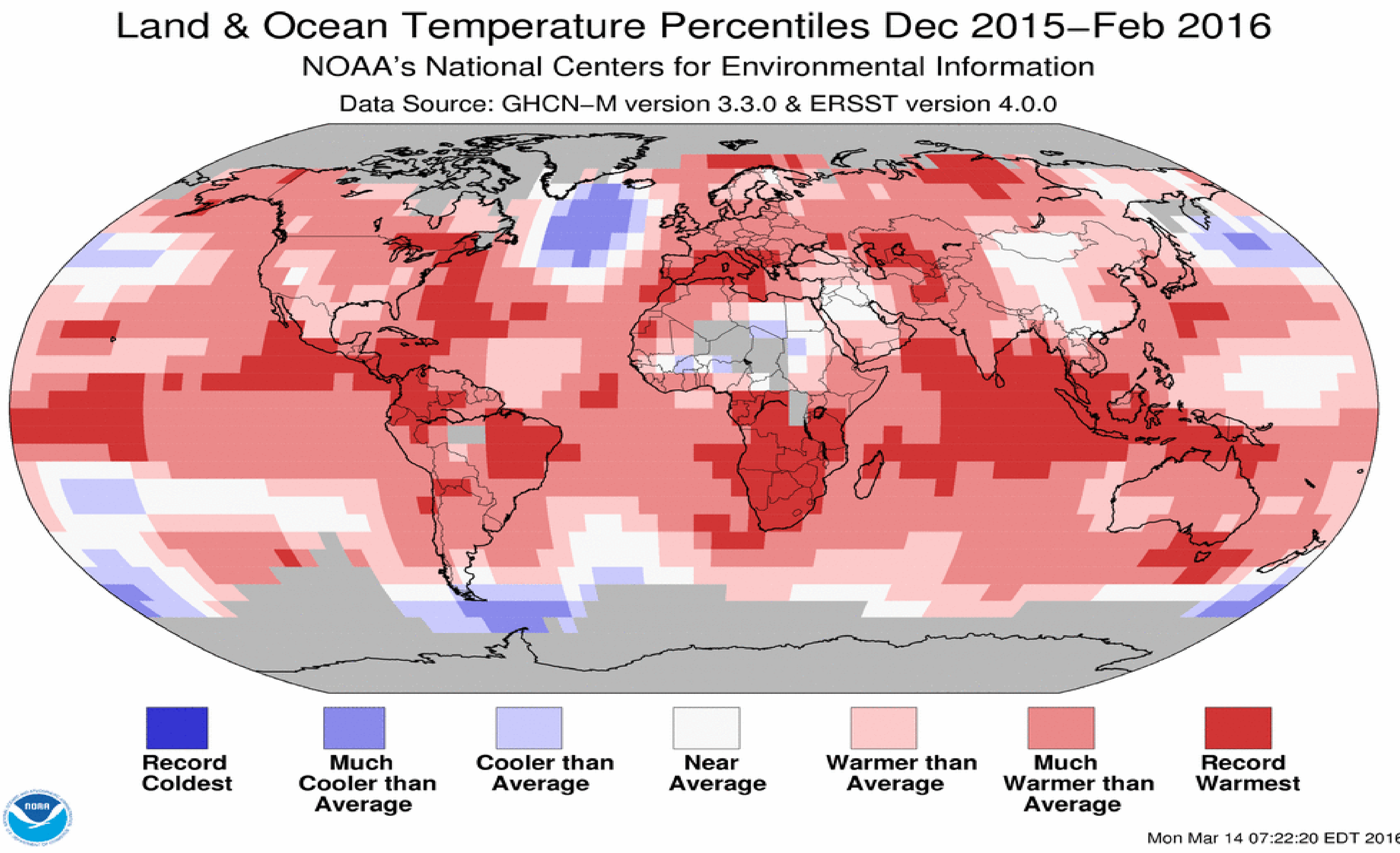
# Hansen *et al.* 2016 (linked here) points to a new era of SuperStorms later this century

- Paleo data indicates remarkably powerful storms driven by the amplified temperature gradient in the Atlantic if the AMOC shuts down...
- The steepening temperature gradient between hotter equatorial waters and colder Greenland meltwater powers **Super Storms**, as evidenced by the last interglacial period.
- Today's developing "cold patch" off Greenland (next slide), where the AMOC descends, is, in Hansen's judgment, the beginning of this process.

# Global Ocean Circulation: Deep Water forms only at 4 places: two off Greenland, and two straddling the Antarctic Peninsula (yellow dots)



**Observed Data. New cold patch (blue) off Greenland, and straddling the Antarctic Peninsula – cold cap of low density fresh water is now inhibiting deep water formation**



**These ~1,000 ton boulders were tossed up from the shallow ocean offshore during the Eemian Interglacial in the Bahamas by Super-Storms, powered by the same AMOC shutdown we may be initiating now. Caption includes "chevron ridges" … (next slide)**

Fig. 1. Two boulders (#1 and #2 of Hearty, 1997) on coastal ridge of North Eleuthera Island, Bahamas. Scale: person in both photos = 1.6 m. Estimated weight of largest boulder (#1, on left) is ~ 2300 tons.

Enormous boulders tossed onto an older Pleistocene landscape (Hearty, 1997; Hearty et al., 1998; Hearty and Neumann, 2001) provide a metric of powerful waves at the end of stage 5e. Giant displaced boulders (Fig. 1) were deposited in north Eleuthera, Bahamas near chevron ridges and runup deposits (Hearty, 1997).

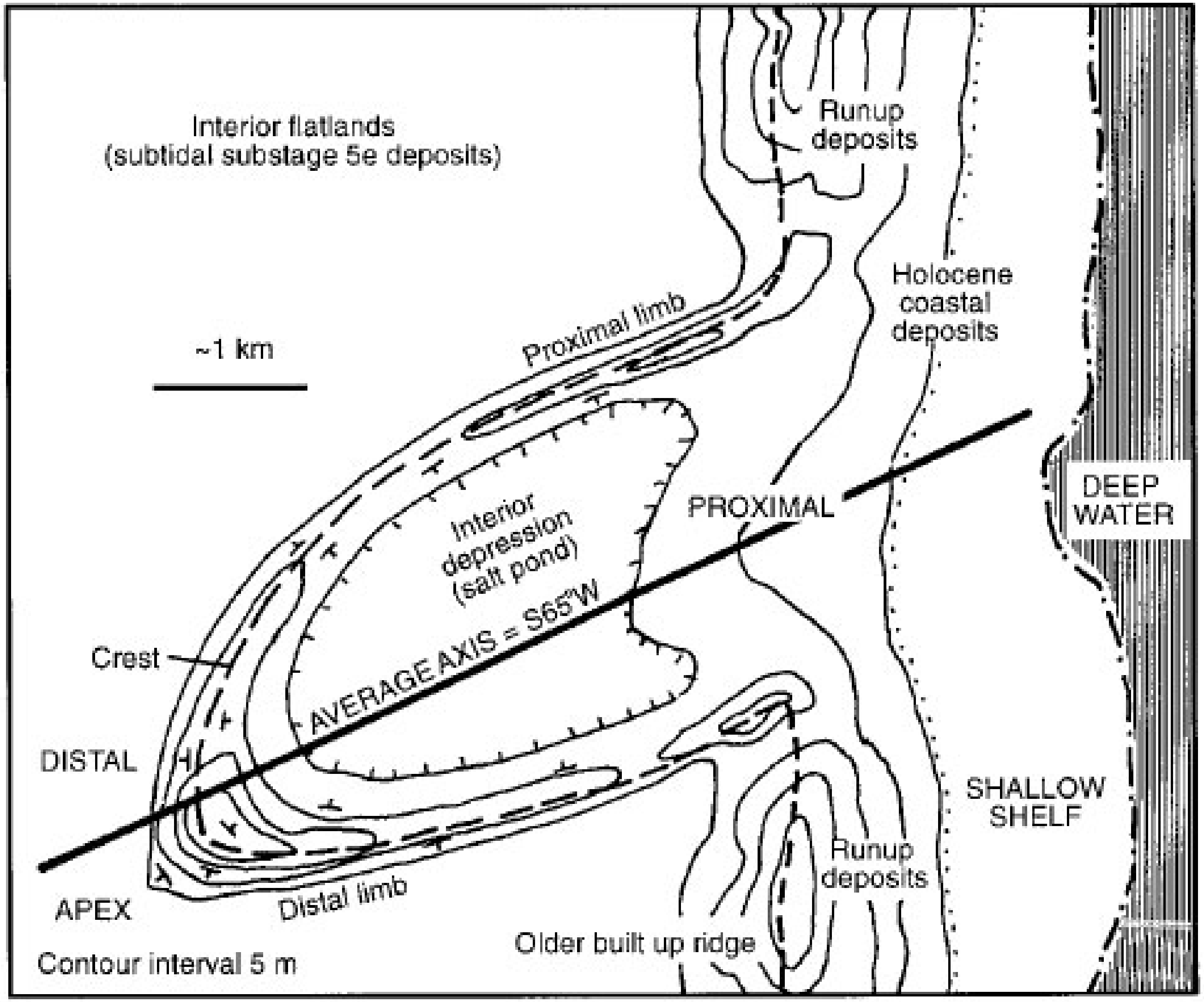
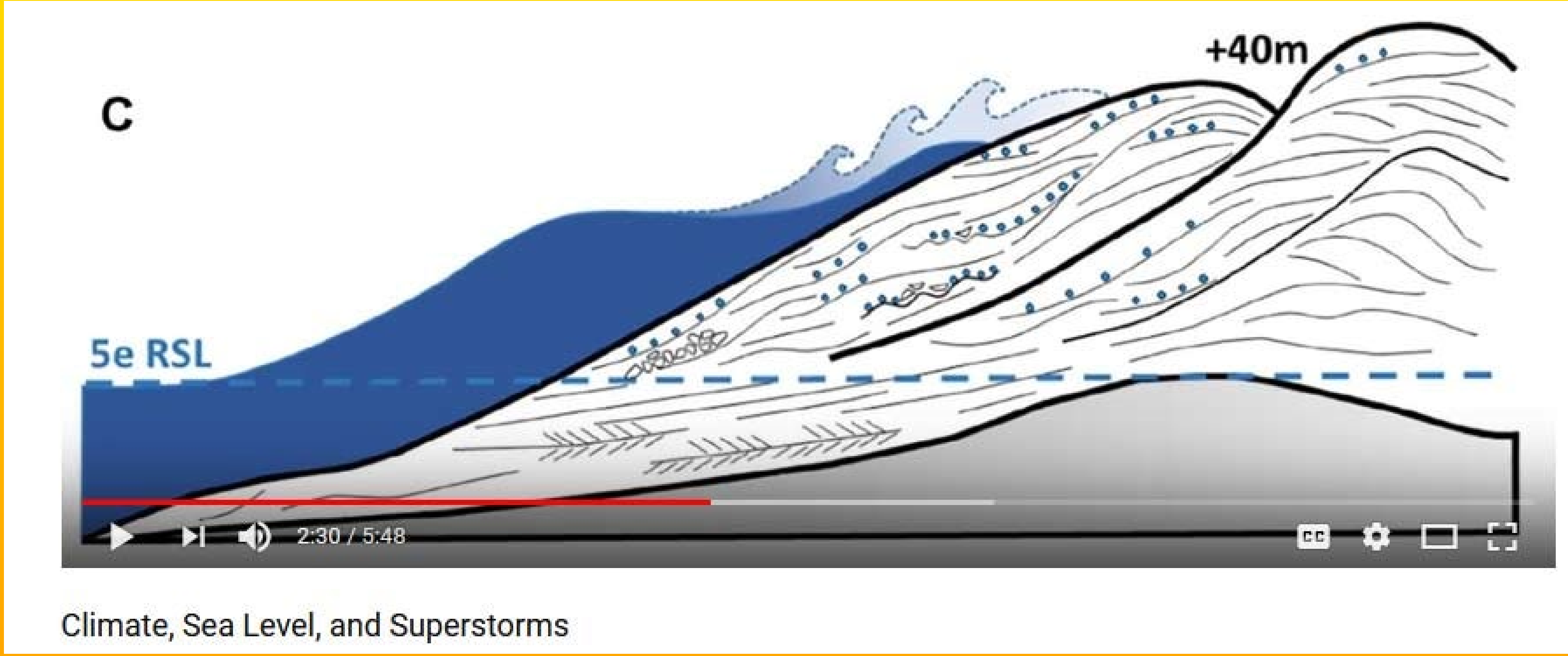



FIG. 1. Schematic map of chevron beach ridge.

**Giant Super-Storm waves of the Eemian created chevron deposits <u>50 ft high and 2 miles long</u>, when washing back to sea. These are all along the shorelines of the Bahamas. <u>Some run-up deposits are as high as 43m, requiring waves nearly ~200 ft in height to create them</u>.**

# Here is a recent [6 min video](#) on this, from Yale Climate Connections



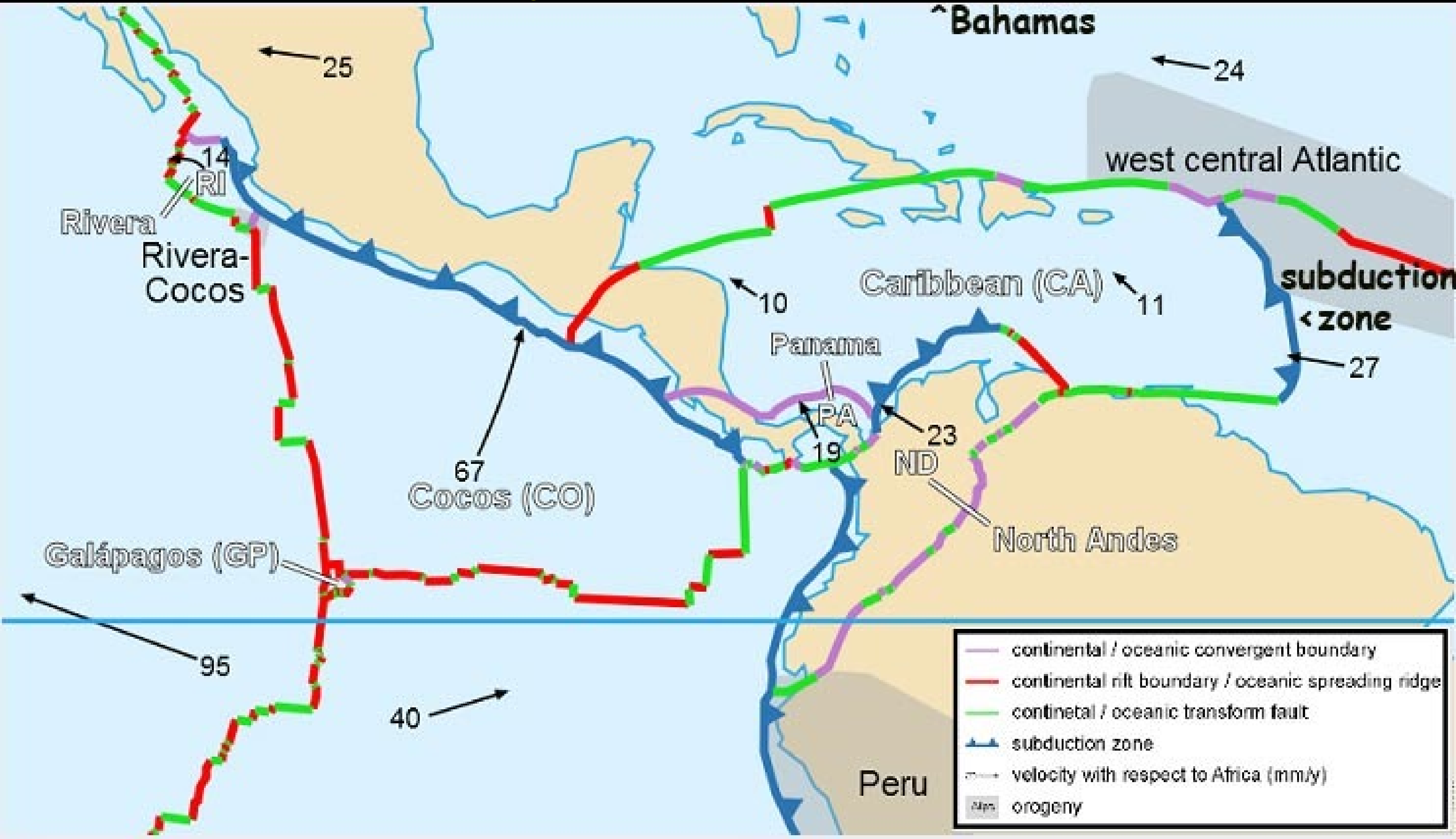

# The waves required for such 43m high run-up deposits… are ~ 170 ft high

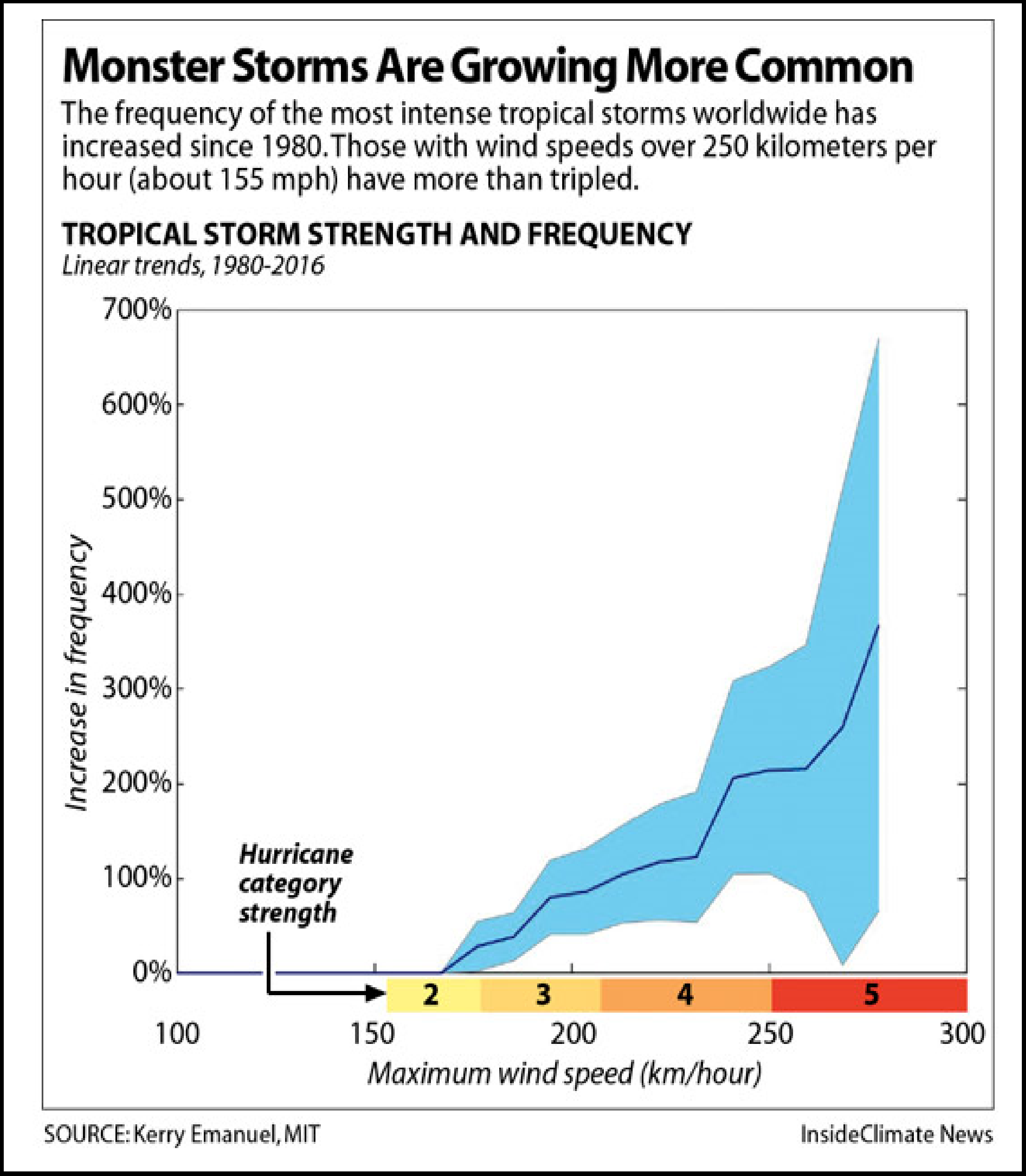
# Remember the waves in the film *"Interstellar"*? They're about the same height

# Some find the strength of storms which could do this hard to believe, and wonder if maybe tsunamis brought them up

- These are clearly boulders and chevron patterns; The debris matches the rock types off the bottom of the nearby ocean, and not the land on which they unconformably sit… **more details here.** Still, healthy skepticism is a good thing!
- But… the tsunami hypothesis makes little sense, since tsunamis are associated with large **subduction zones or extremely massive landslides…**

There are no such subduction zones close enough to the Bahamas. The nearest subduction zone of any kind is a very short and weak zone southeast of Cuba. And any events due to the subduction zone north of Colombia would be shielded from the Bahamas by Cuba and Haiti. The Canary Islands tsunami fears highlighted in a PBS Nova TV program, were later debunked. And there is no evidence of any such landslides in the Eemian Period here



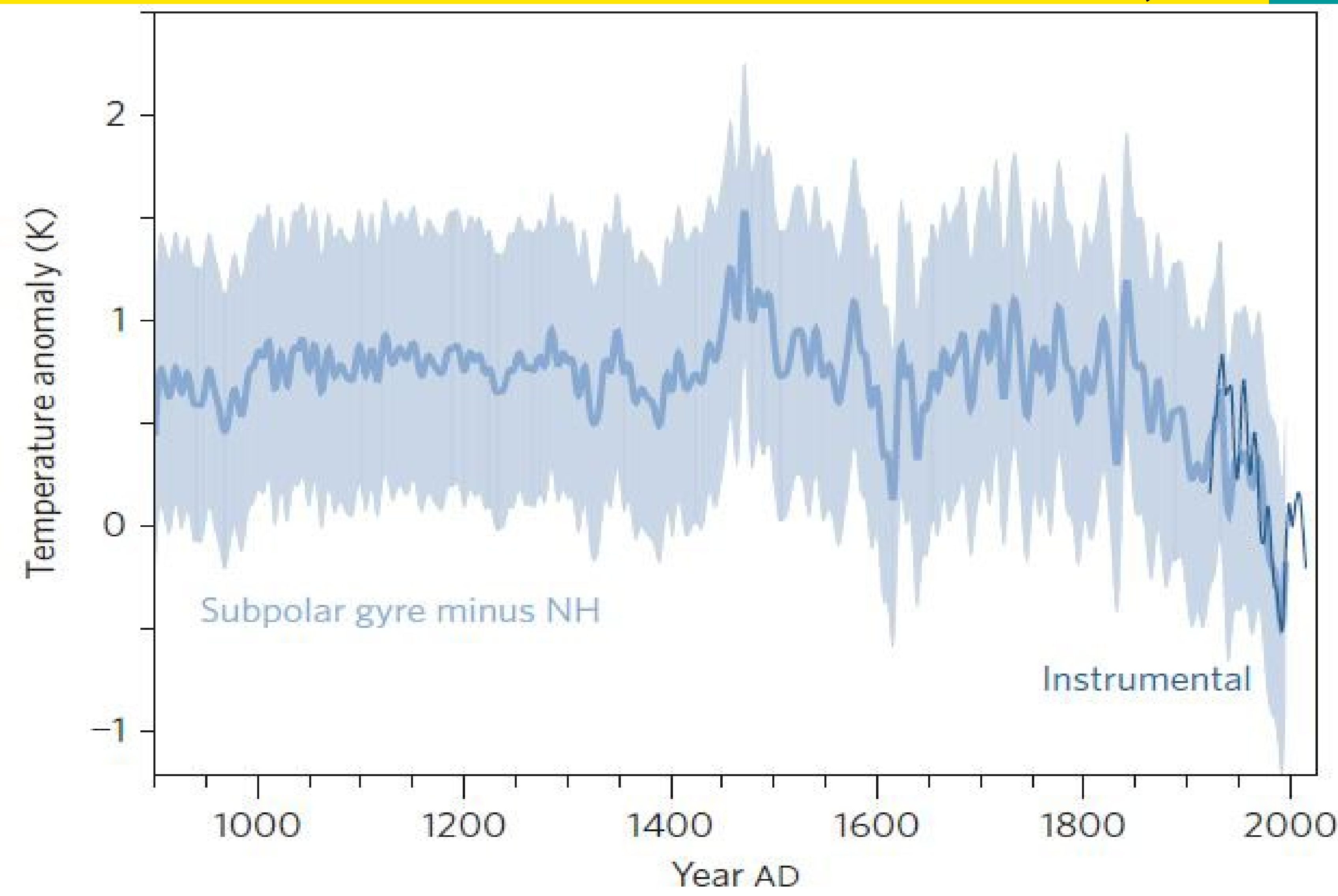



**It appears the process has begun…**

# Could the Global Ocean Circulation Really Shut Down?

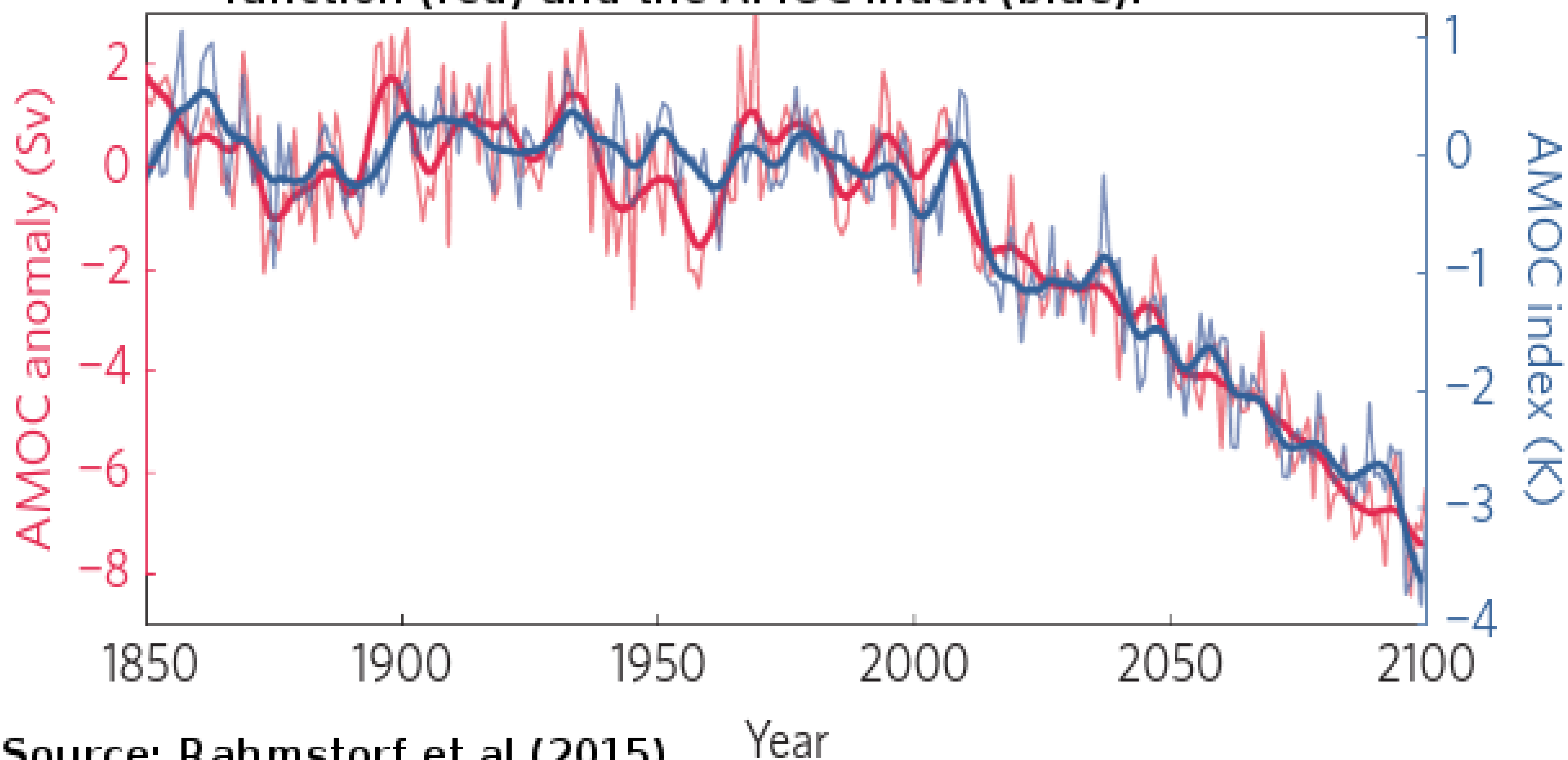
- **Yes.** Climatologist James Hansen thinks it's likely, in fact. The IPCC AR4 thought the AMOC would weaken but not halt in this century, but the new data (below) is indicating a more rapid decline than their models expected. **Again, IPCC under-estimation is evident.**
- It's concerning that the current greenhouse forcing is far stronger than any prior Milankovich climate forcing, including the Eemian interglacial ($CO_2$ at 280ppm), yet the Eemian Period did see global ocean circulation shut down, and with temperatures at those we are already at, now, today.
- **Indeed, the Atlantic Meridional Overturning Circulation (AMOC), which is the only portion of the global currents on which we now have good data as of 2015, has already weakened…**

**Time series of the temperature difference between the subpolar North Atlantic and the entire northern hemisphere, which can be interpreted as an indicator of the strength of the Atlantic circulation. From Rahmstorf *et al.* 2014, see here**



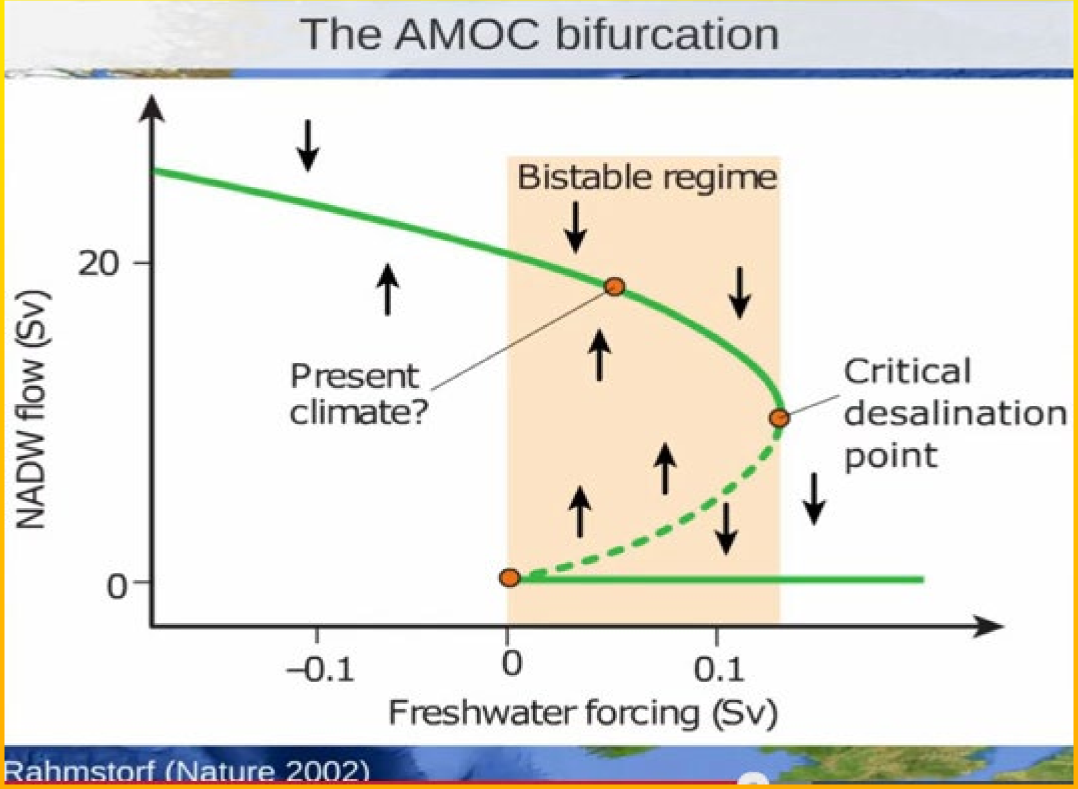
**The strength of the AMOC is declining, and predicted to continue (Rahmstorf *et al.* 2015). When will Super-Storms Arrive? Since the cold melt surface has clearly begun, it'll probably be a gradual ongoing increase in storm intensities. Perhaps the Hurricanes of '17 and '18 are a small taste.**

Time series of the maximum overturning stream function (red) and the AMOC index (blue).




Source: Rahmstorf et al (2015)

# Rahmstorf *et al.* (2002) Had Already Shown the System Stability Trajectory




We're already in a salinity regime where there are two stable solutions, one being total shutdown. If melt increases and salinity declines further, a critical desalinization point is reached and the current shuts down. Then, only drastic re-salinization (re-freezing Greenland) can push it all the way back to a point where the current can resume, and that would take many centuries even if temperatures dropped immediately, according to James Hansen.

# A New Study by *Liu et al.* 2016 shows how unstable the AMOC is

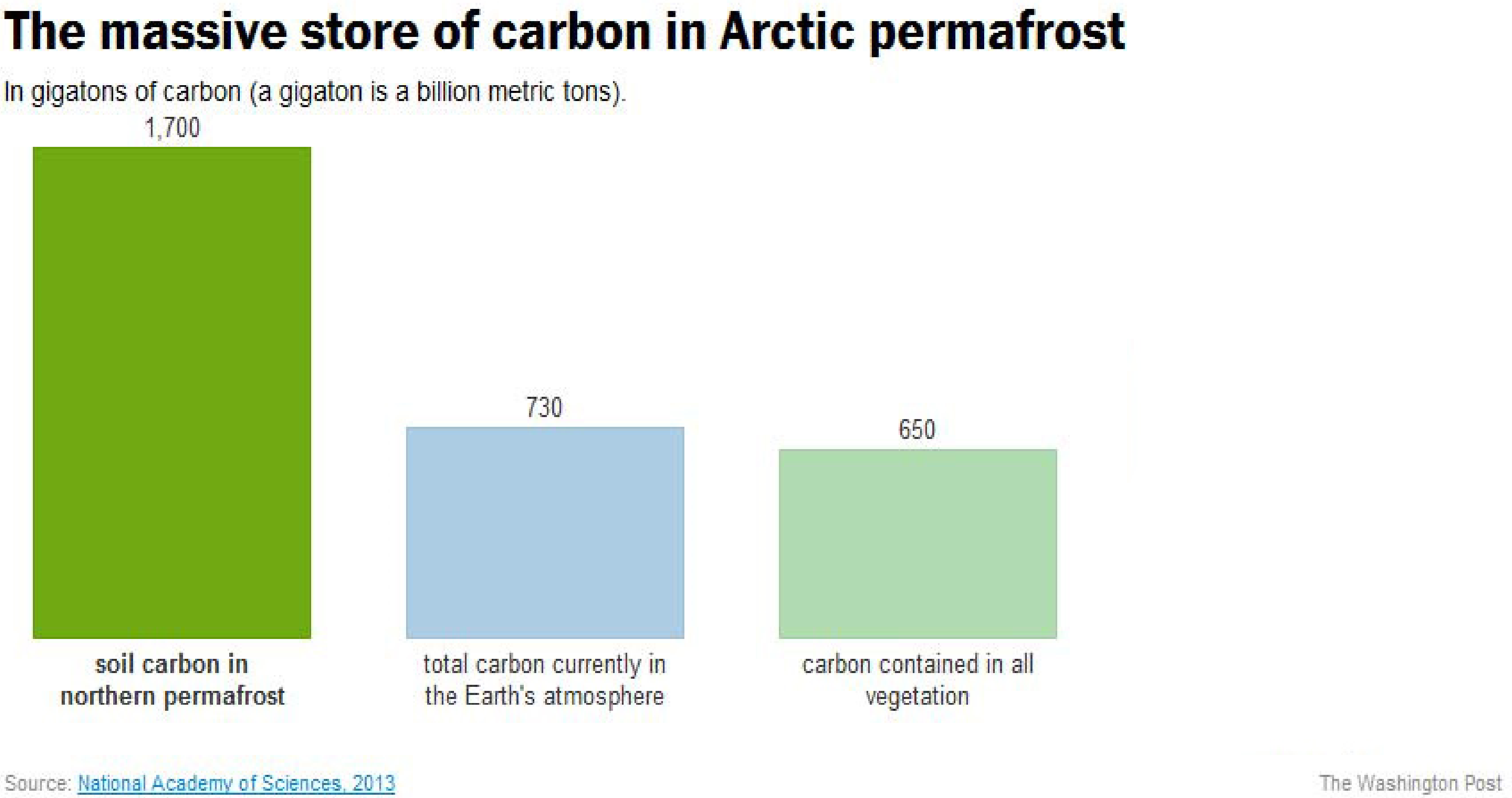
- Prior studies had assumed that freshwater from rains flowed from the Southern Ocean around Antarctica and into the South Atlantic, but actual observations are showing the opposite direction of freshwater flow.
- This has the effect of making the surface North Atlantic less salty and makes even weaker the AMOC's ability to densify around Greenland and sink through the Thermocline.
- They point out that they did not consider Greenland meltwater freshening of North Atlantic waters, as **Hansen *et al.* 2016** did, and so these two different effects actually should be **added** together
- **Thus, hopes that the observed dropping AMOC strength might be just an oscillation and not a secular trend, are fading.**

# 10. Carbon Release from the Permafrost and Methane Clathrates

# How much methane carbon is there?

- Exact amount is not known, but we can estimate…
- **Arctic permafrost contains roughly twice the carbon as is already in the entire atmosphere**.
- Therefore, if ALL of it becomes CO2 and reaches the atmosphere, it alone would triple the CO2 content, from 400 to 1,200 ppm (until some uptake by ocean/land)
- Is that possible? How long does thaw take?

# Northern hemisphere permafrost has more than double the carbon content of our atmosphere



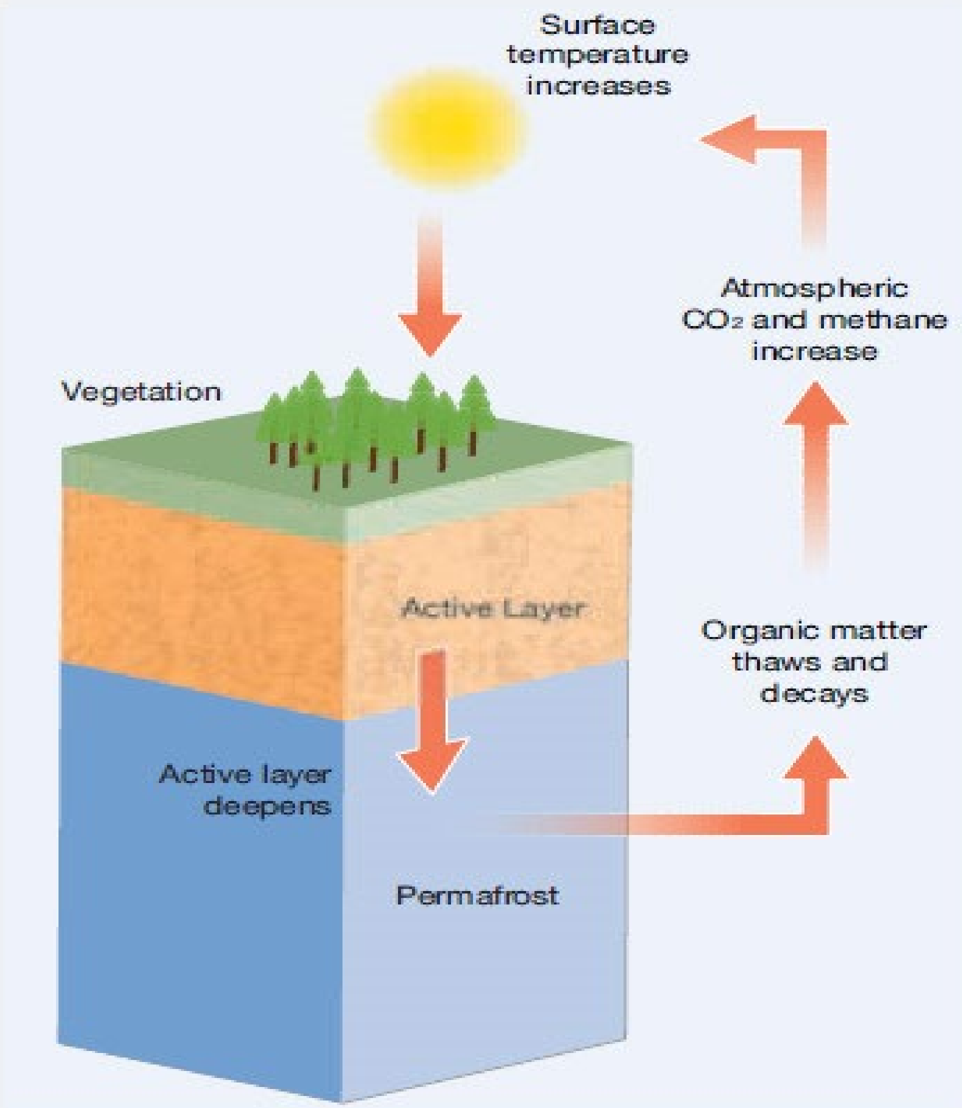



**Figure 21:** The permafrost carbon feedback is an amplification of surface warming due to the thaw of organic material currently frozen in permafrost, which will then decay and release $CO_2$ and methane into the atmosphere.

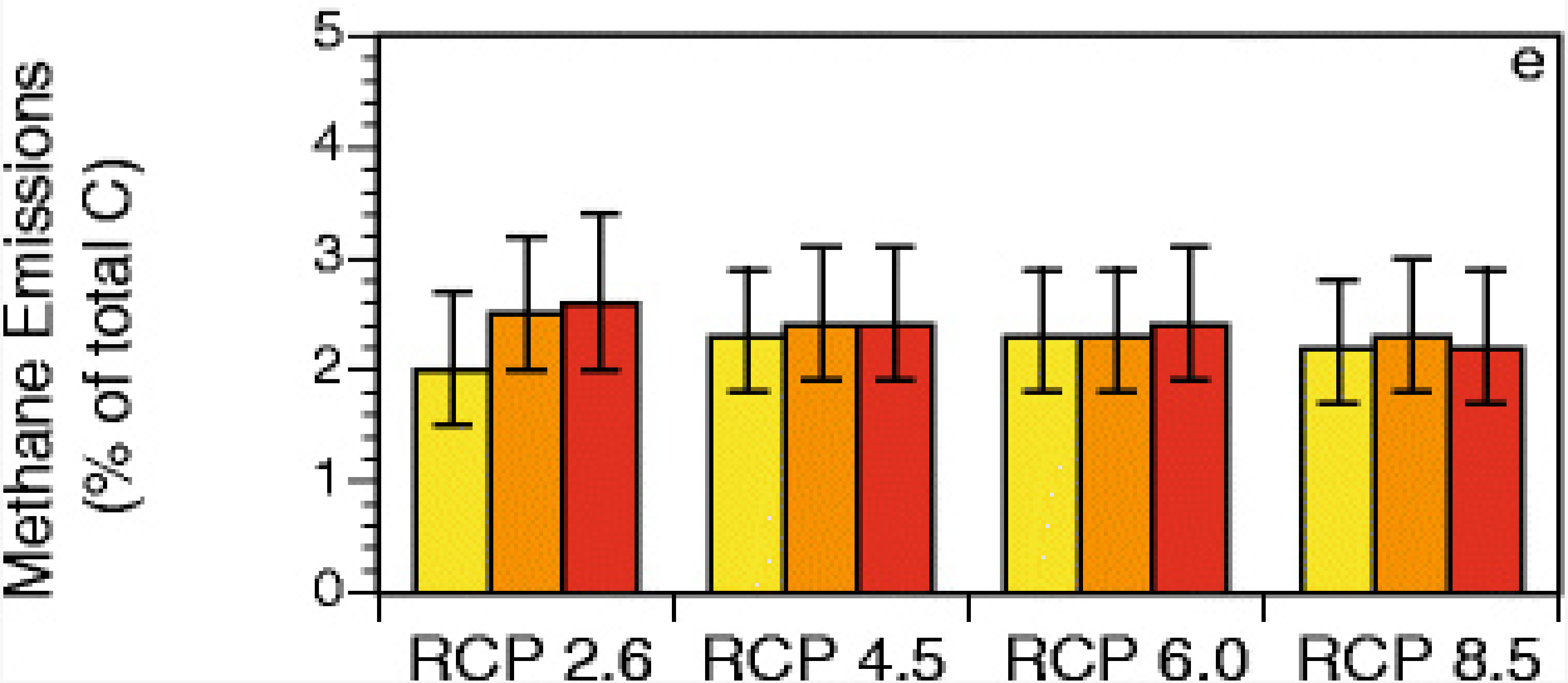
# The permafrost carbon feedback

is **irreversible on human time scales**. With less near-surface permafrost, the burial mechanism described above slows down or stops, so there is no way to convert the atmospheric CO2 into organic matter and freeze it back into the permafrost.

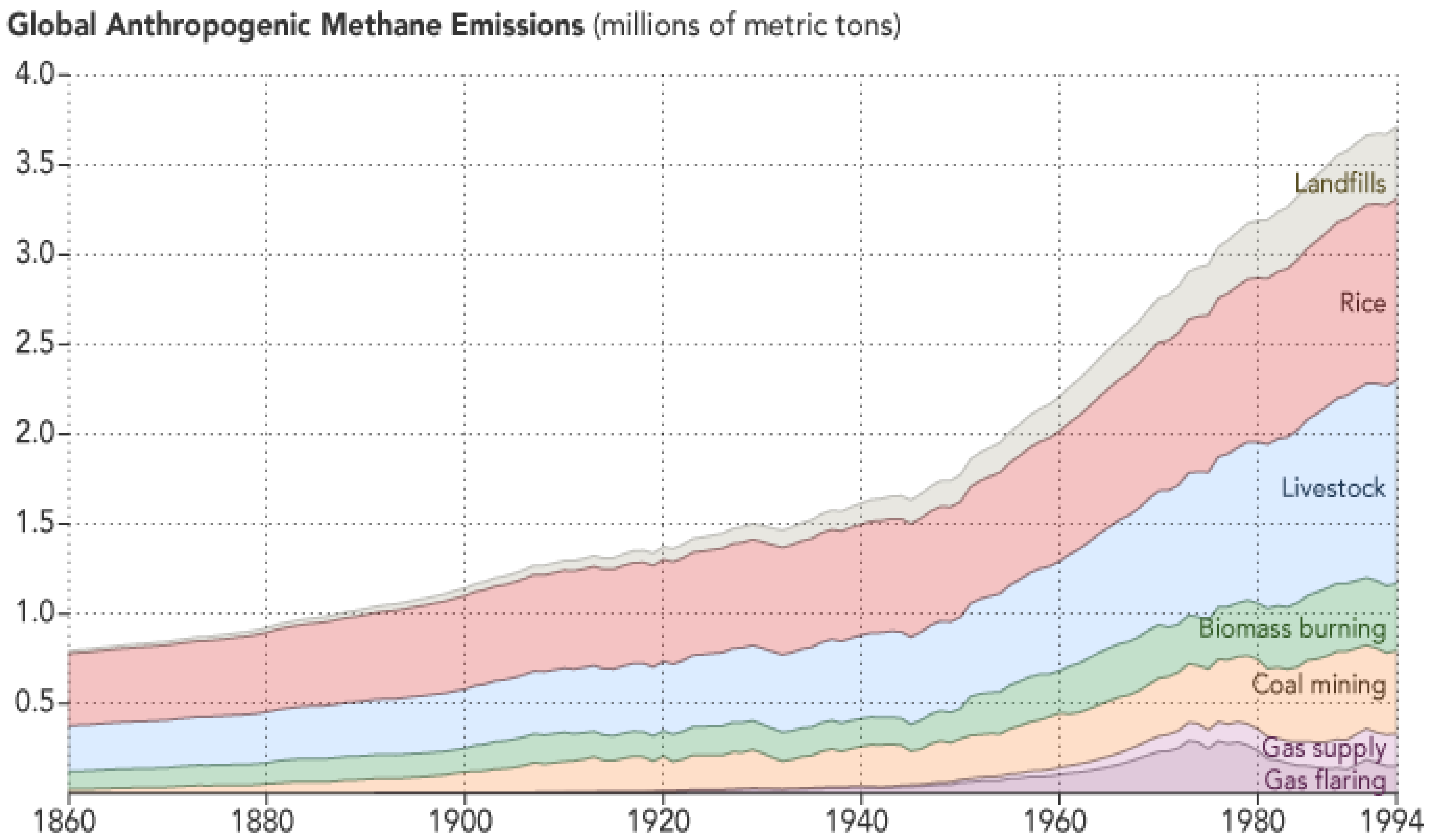
Warmer conditions and increased atmospheric CO2 will enhance plant growth that will remove CO2 from the atmosphere (Friedlingstein *et al.* 2006), but this can only to a small degree compensate for the much greater carbon emissions from thawing permafrost. Warmer conditions could promote peat accumulation, as seen after the end of the last ice age, but it is not clear if this would remove enough CO2 from the atmosphere to compensate for CO2 released from thawing permafrost.

**The effect of <u>permafrost carbon feedback on climate has not been included in the IPCC Assessment Reports.</u> None of the climate projections in the IPCC Fourth Assessment Report include the permafrost carbon feedback (IPCC 2007).** Participating modeling teams have completed their climate projections in support of the Fifth Assessment Report, but these projections also do not include the permafrost carbon feedback. **<u>Consequently, the current IPCC Fifth Assessment Report also does not include the potential effects of the permafrost loss</u>.**

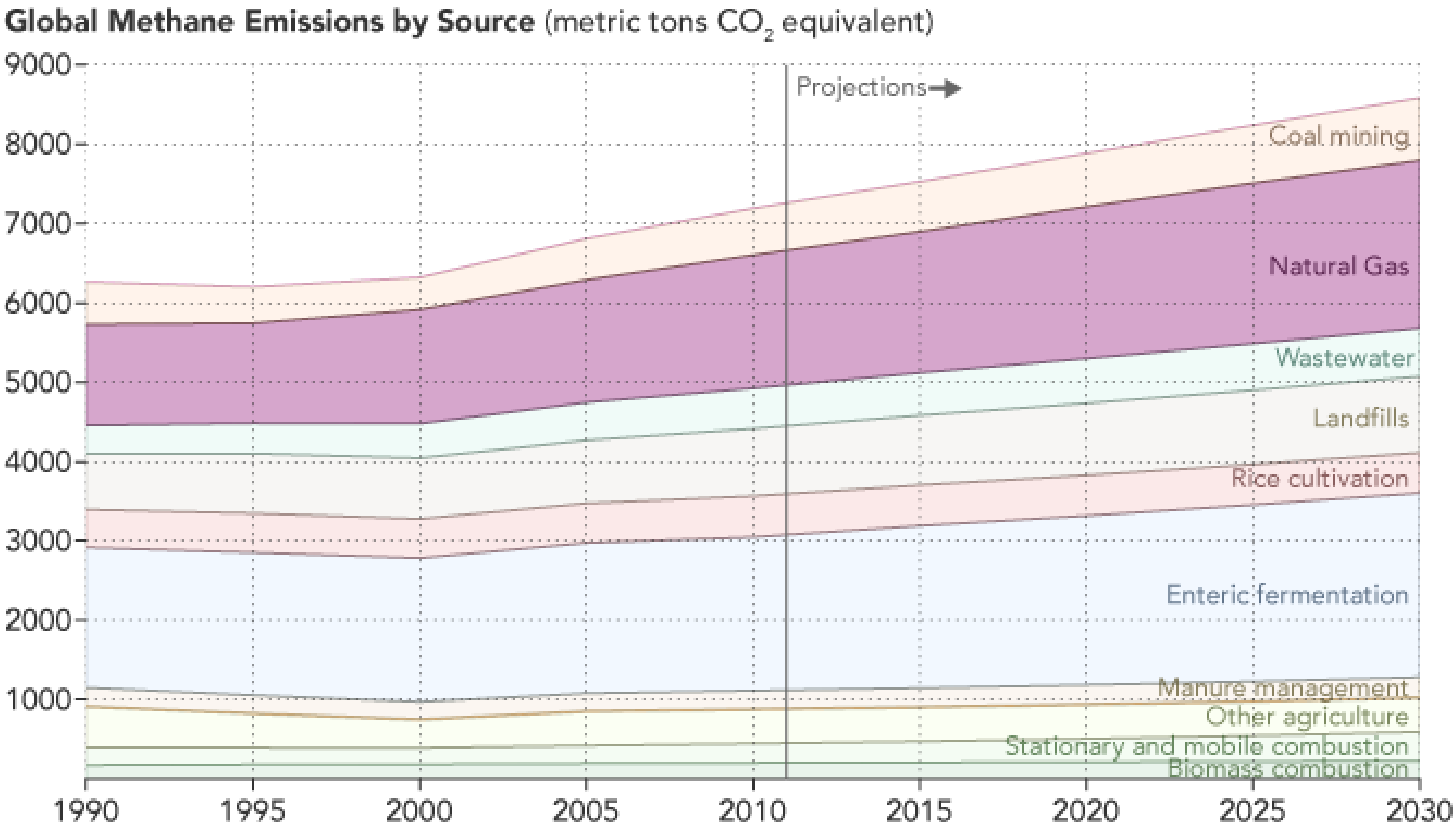
**[Schuur *et al.* 2013](), surveyed dozens of permafrost experts, found a consensus that 2.3% of the permafrost's emerging carbon to be in the form of methane - regardless of human emission scenario. <u>(bar colors are for year 2040, 2100, 2300) (but new research says it may be ~4x higher)</u>**



**Even neglecting the indirect Arctic methane - directly caused anthropogenic methane emissions are rising rapidly. Biggest increases are in rice growing and livestock ([NASA](NASA)). This is through 1994… Next slide continues forward in time**



**As in last slide, these estimates are from source reporting. A very different (and more objective and honest??) approach is to study atmospheric concentrations and carbon 13/12 ratios. Total Anthropogenic methane emissions predicted to grow at 1.08%/year from 2000 to 2030. (NASA)**



## An Ice-free Arctic Ocean warms the entire Arctic as far as 1500 km inland (Lawrence *et al.* 2008), including the majority of Permafrost carbon

- **Vaks *et al. 2013*** *(and **full text**)* had an insightful way to determine the state of the permafrost in Paleo climate – when ground above a limestone cavern is frozen, the speliothems cannot grow. But when melted, dripping water through the soil to the cave ceiling allows them to grow.
- $O^{18}/O^{16}$ ratios tell temperature at the surface..

**Rapid loss of Arctic Ocean ice sends temperatures across permafrost lands upward, as far as 1500 km south of the Arctic coast. Arctic Ocean ice is, in fact, already in rapid loss right now ([Lawrence *et al.* 2008]). <u>This is a key tipping point</u>: <u>Keeping the Arctic Ocean Ice Cap is Essential to Preserve Climate</u>**

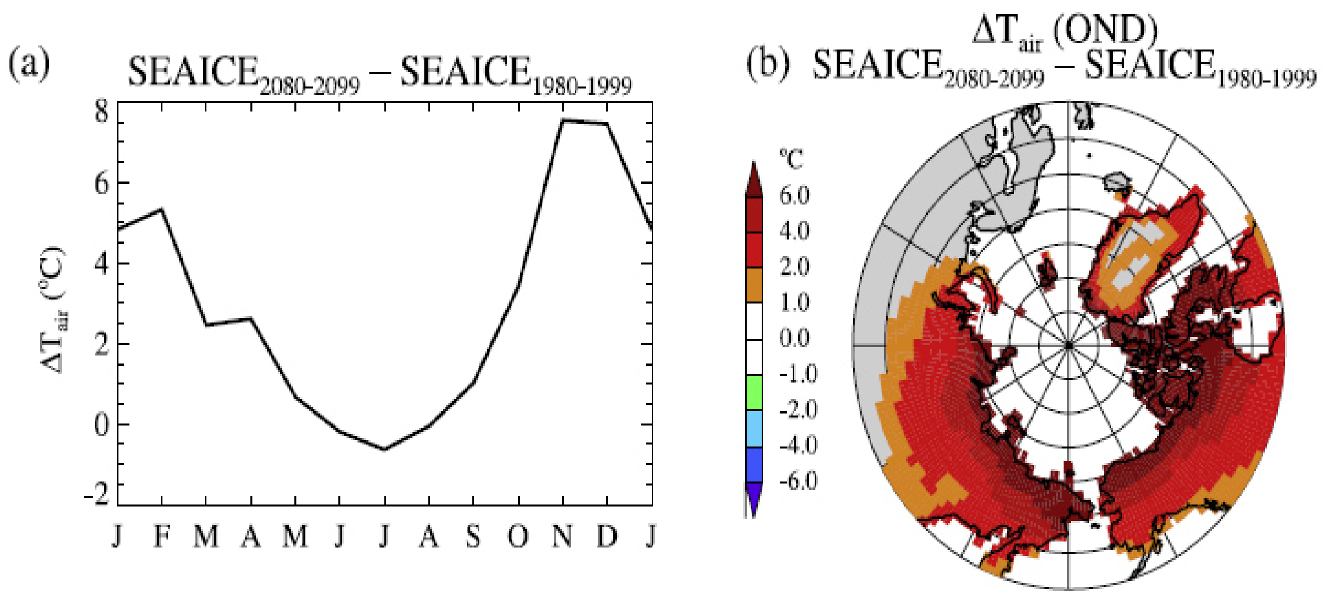
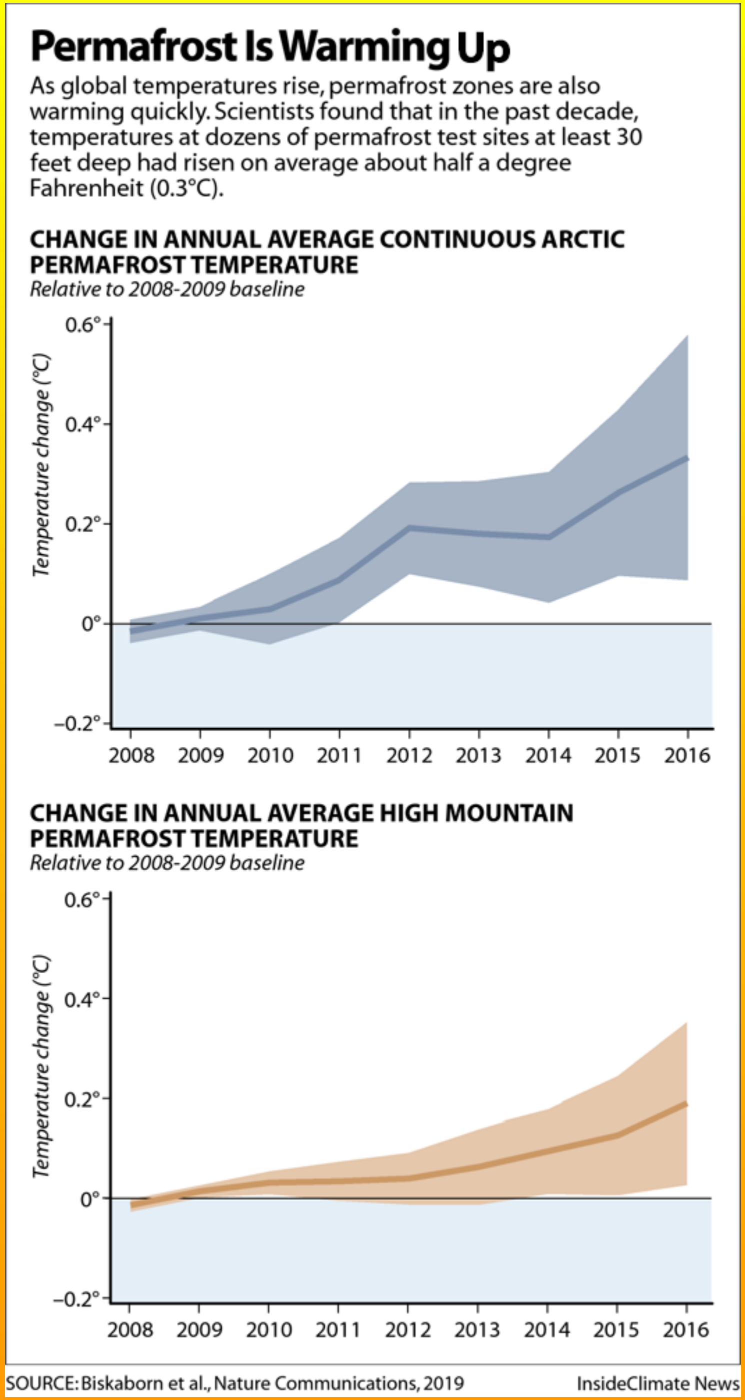



**Figure 2.** $\Delta T_{air}$ between simulations with prescribed 2080–2099 sea-ice conditions obtained from CCSM3 A1B 21st century ensemble and prescribed 1980–1999 sea-ice conditions obtained from CCSM3 20th century ensemble. (a) Monthly $\Delta T_{air}$ over western Arctic land (65°–80°N, 60°–300°E). (b) Map of $\Delta T_{air}$ for OND.

# The Permafrost Thaw Tipping Point is Therefore Close

- Vaks *et al.* 2013 found that Arctic permafrost will melt as far north at +60 latitude once global equilibrium temperature of +1.5C is reached and maintained.
- While his later data questions whether the +1.5 C limit corresponds to a GLOBAL average temperature, because the North Atlantic ocean temperature also affects speliothem growth, the worry remains that observed melt suggests we're already very close to that now.
- We were at +1.21C at the close of 2019 using the old 1880-1910 convention as "pre-industrial" baseline temperature (adopted only because pre-1880 data is poorer).
- **But we are at +1.42C** using the better motivated Schurer, Mann, *et al.* (2017) pre-industrial temperature baseline
- And yet the permafrost is already thawing.

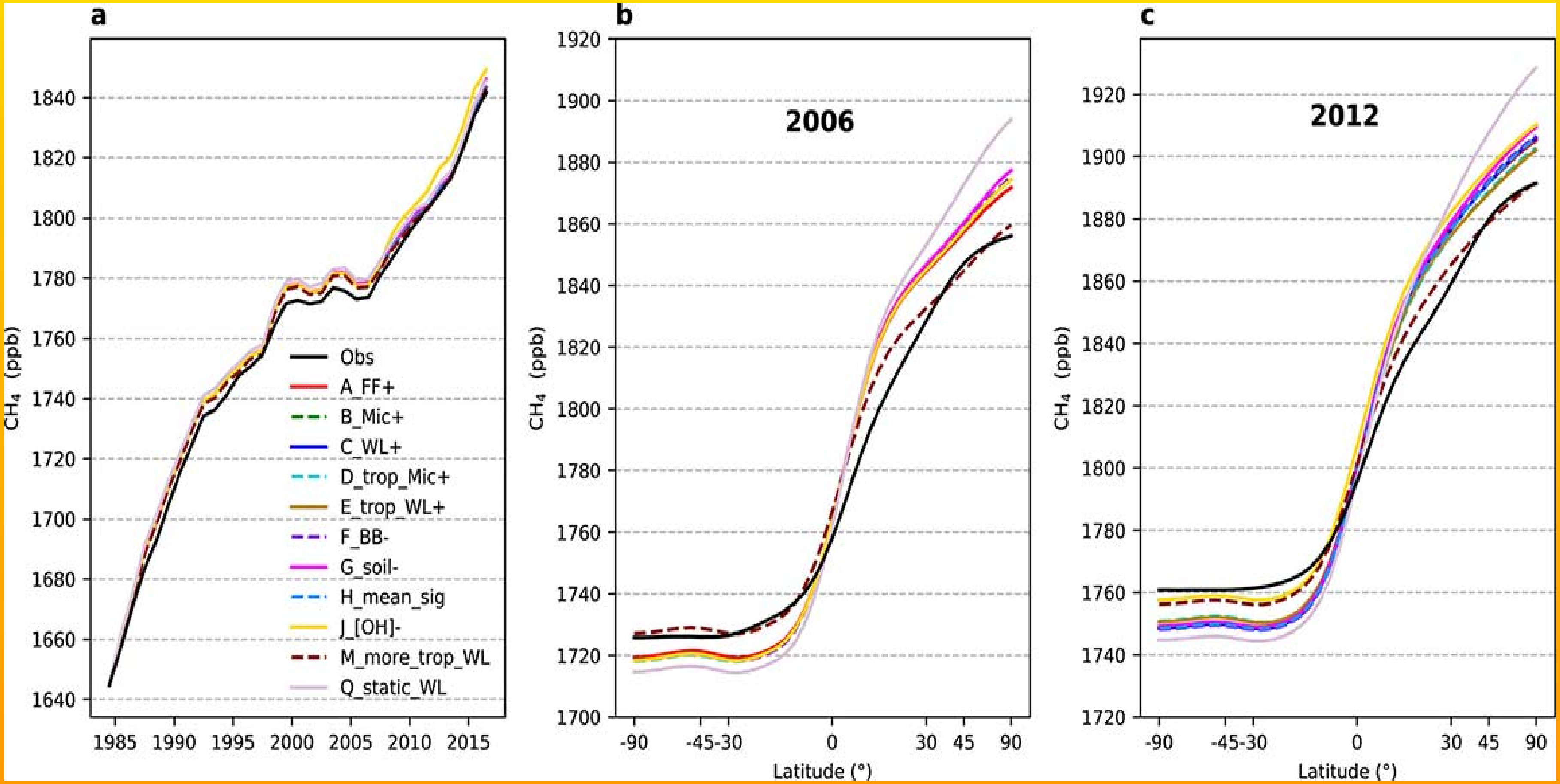



And, in 2020, a new study (Martens *et al.* 2020) suggests that permafrost is indeed close to the tipping point, at 2020's +1.45C. Other new studies are consistent

# How much of rising methane is from such indirect human-caused sources, *vs.* direct human-caused?

- This is a critical question – we can only directly control methane emissions from direct human causation, such as fossil fuel mining.
- We cannot control the permafrost except very indirectly and with a major time lag.
- Global CO2 is up 50% since pre-industrial. But global methane is up over 300% since pre-industrial, despite its ~10 year chemical half-life!

# Atmospheric Methane concentrations are highest in the Arctic, and accelerating (Lan *et al.* 2021). Wetlands methane from thawing thermokarst lakes is a prime suspect, given Walter-Anthony's work.



# Lan *et al.* (2021) conclude direct human emissions by fossil fuels is **not** the main cause of accelerating CH4 emissions.

- *"The (isotope) data pointed to microbial sources, such as natural wetlands, shallow lakes and rivers, and human-managed sources like livestock, landfills, rice paddies, and wastewater treatment.*
- *"Our analysis indicates that methane emissions from fossil fuels are unlikely to be the dominant driver of the post-2006 increase," said Lan. "The long-term change can't be explained by a reduction in the rate at which the atmosphere degrades methane either." (source). **However, a new study finds this conclusion is changing…***

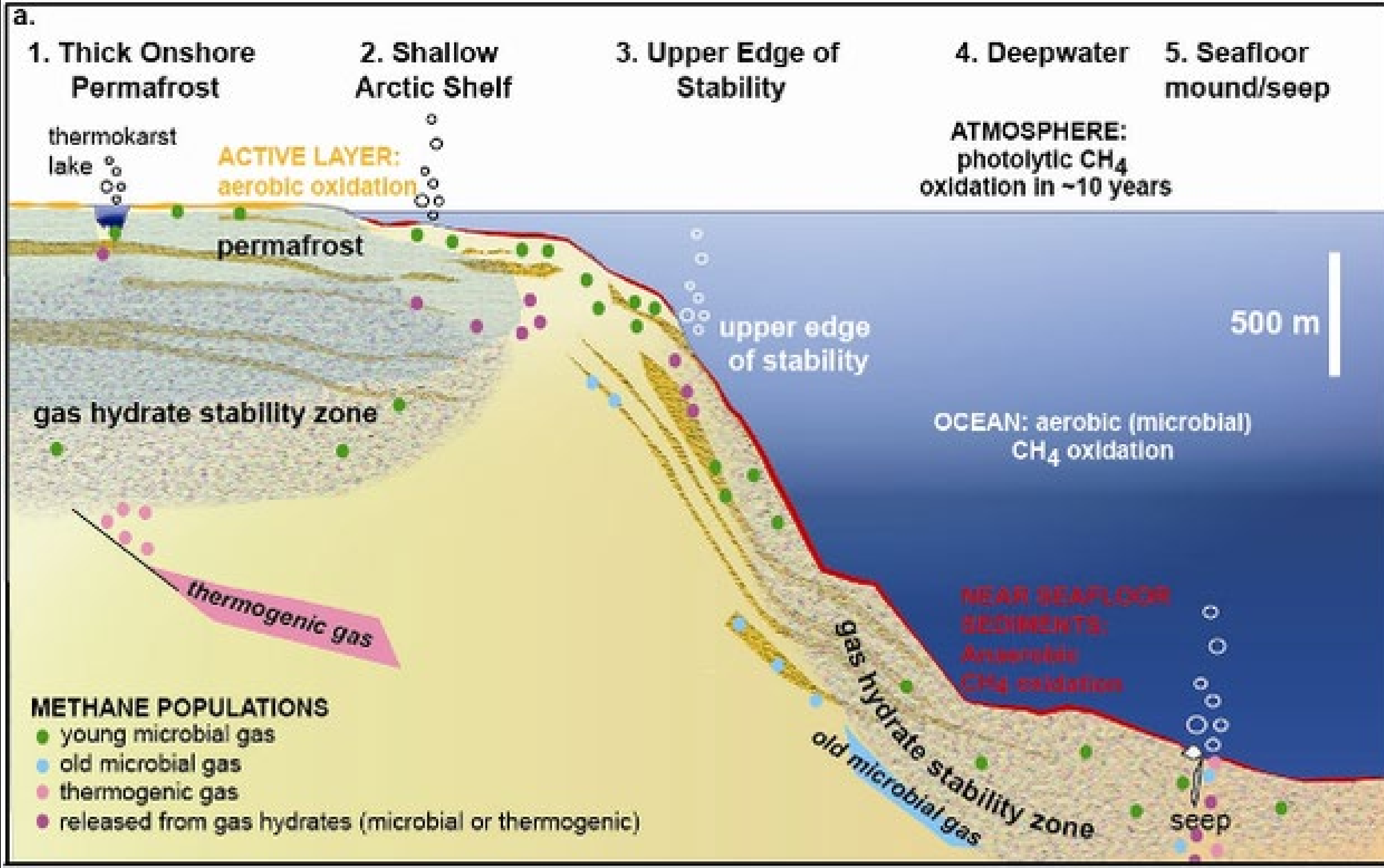
# **<u>Reducing</u> fossil fuel burning actually causes rapid atmospheric methane <u>increase</u>**

- CoVid Pandemic recession-induced drop in fossil fuel burning (<u>Allen 2022</u>), and wetlands increases are equally the culprits <u>Peng *et al*. 2021</u>.
- NOx accounts for 85% of methane destruction, but NOx is primarily produced by FF burning, and also modern agriculture.
- Peng *et al*. find a **<u>mere 20% reduction in NOx then doubles the rate of atmospheric methane net production</u>**

# Permafrost Thawing

# Permafrost coastal instability

# Methane Deposits: Continental Clathrates, Permafrost, Arctic Lakes, Subsea Clathrates




Ruppel, Nature Knowledge, Hydrates/Climate, April 2011

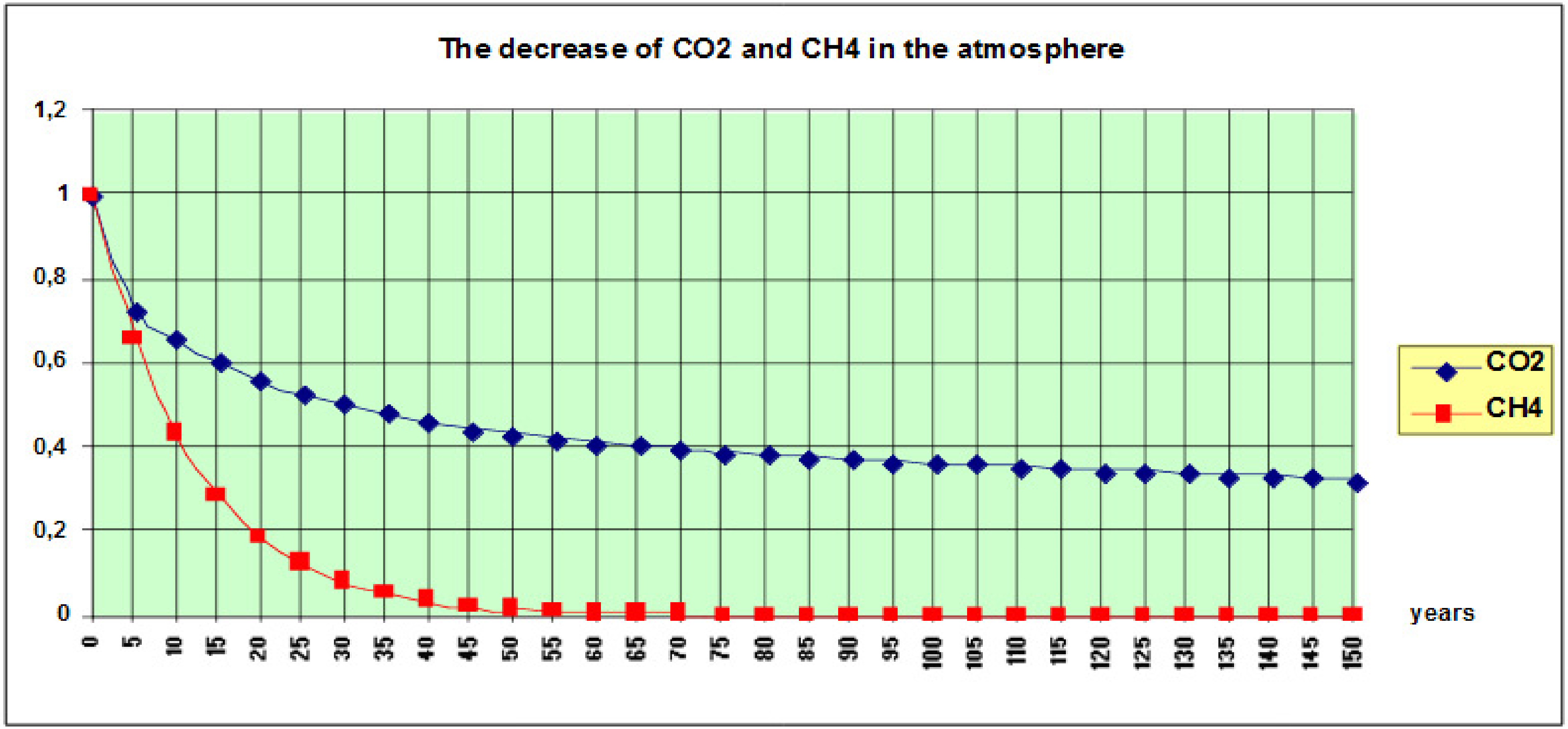
- **As we saw, short of forced removal of CO2 from the atmosphere, temperatures will not go back down, even if we halt all human emissions.**
- **We are already most of the way to an ice-free summer Arctic Ocean**
- **Nobel Prize winning Physicist Steven Chu on permafrost methane and climate (1:35 video)**
- Arctic will become major carbon source *via* thawing permafrost by 2020's **Shaefer *et al.* (2011)** and summarized **here**. Finds estimated 30-60% of permafrost will be melted and its methane released by year 2200.
- **This may be too optimistic: see newer research by Abbott *et al.* 2016, a few slides ahead.**

A new study (**Schuster *et al.* 2018**) finds there is more toxic mercury stored in the permafrost than **the entire ocean, land, and atmosphere combined, multiplied by two**. How much will be released to the environment as it thaws, is not yet clear.

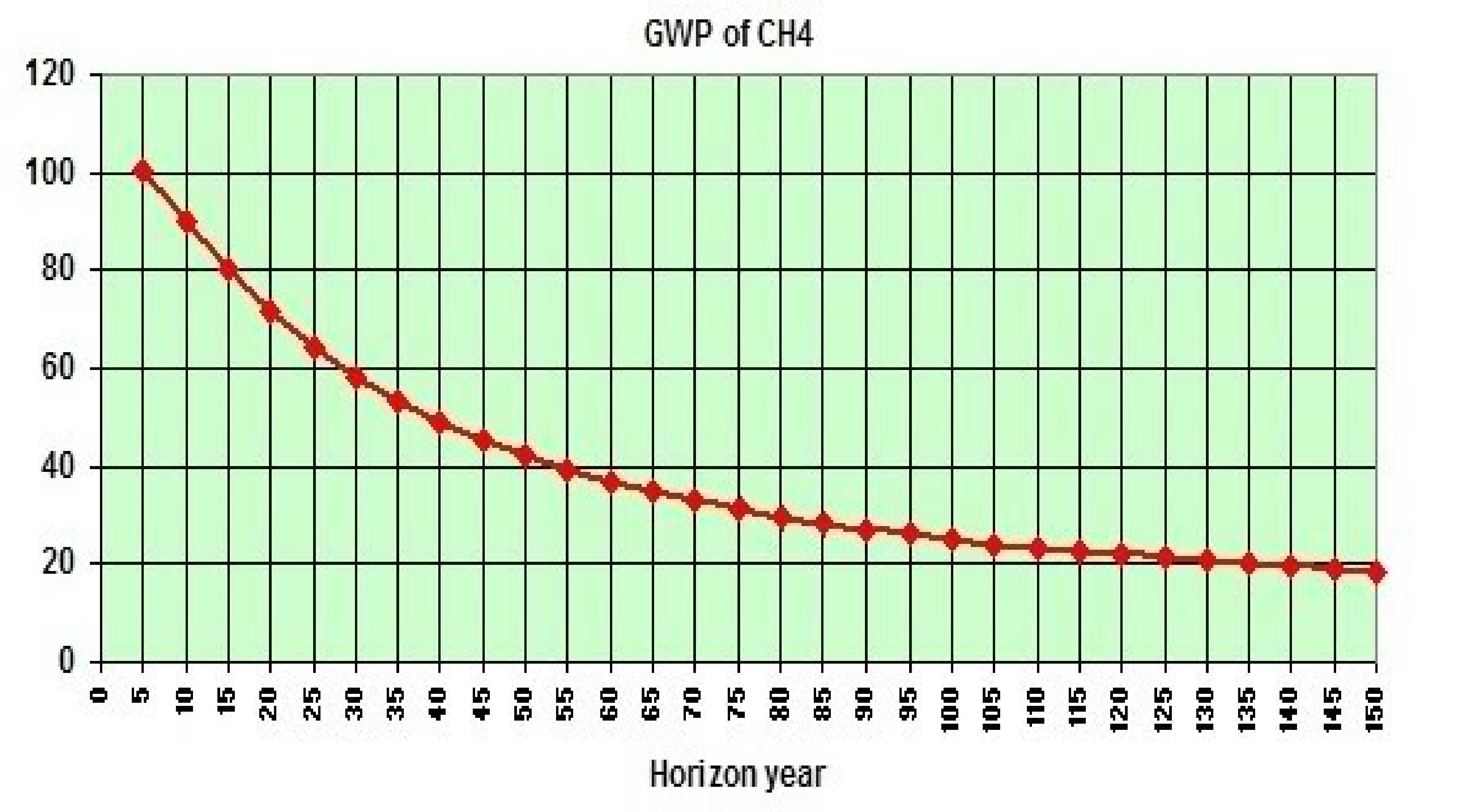
# Arctic Methane: Small but growing contributor?

- Arctic carbon, thawing permafrost: Microbes will eat some, converting it to $CO_2$ and to methane both
- Sunlight will do the same, and this is actually one of the rare negative feedbacks, as thawing ice will uncover more tundra earlier and expose it to sunlight
- Methane will oxidize to $CO_2$ and $H_2O$, over decades.
- As of 2015, **Arctic methane release was believed to be a poorly determined but small fraction of total global methane emissions**, which are mostly from lower latitude sources; fracking, livestock, and wetlands.

**CO2 is absorbed slowly by the oceans and land, while methane converts to CO2 and water vapor more quickly. Graphs show what a given ton of each, deposited to the atmosphere, does over time ([Dessus *et al*. 2008]) but does not include crippled "CO2 fertilization" or later research showing amplifying soil losses on plants' ability to pull CO2**



# Methane converts to $CO_2$ and $H_2O$ with a half-life of 12 years. But the resulting "GWP" = Global Warming Potential" = the climate radiative forcing of methane relative to $CO_2$ (Dessus *et al*. 2008) decays much more slowly; half-life ~40 years



**Siberian Methane Craters:** Pingos melting and filling with deep methane, then exploding and leaving large craters. While it would take many many thousands of such craters to be a significant force in climate…

# … more are being discovered all the time

# In 2017, Scientists are Discovering…

- …Over 7,000 new domes filled with methane and “are ready to explode”, in the Yamal and Gydan Peninsulas alone. Methane explosion craters continue in 2017

# Is The Thawing Permafrost Incorporated into the IPCC Assessment Reports and Projections?

- **No.**
- "*The concept is actually relatively new,"* says Dr. Kevin Schaefer of the National Snow and Ice Data Center at the University of Colorado in Boulder*. "It was first proposed in 2005. And the first estimates came out in 2011."* Indeed, the problem is so new that it has not yet made its way into major climate projections", Schaefer says.
- **"None of the climate projections in the last IPCC report (AR5 in 2013) account for permafrost," says Schaefer. "So all of them underestimate, or are biased low."**
- ***It's "a true climatic tipping point, because it's completely irreversible,"*** **says Schaefer.** ***"Once you thaw the permafrost, there's no way to refreeze it." (source)***

# New in 2016 – Methane is released even more in the “cold season” (fall, winter, and spring) than in the summer thaw season

- Climate models have been assuming that Fall and Winter methane emissions in the Arctic were negligible due to freezing.
- Zona *et al.* 2016 are the first to **measure** Fall and Winter methane emission levels across the Arctic, and find they are in fact at least **half, or most,** of all annual methane emission. This is highly significant.

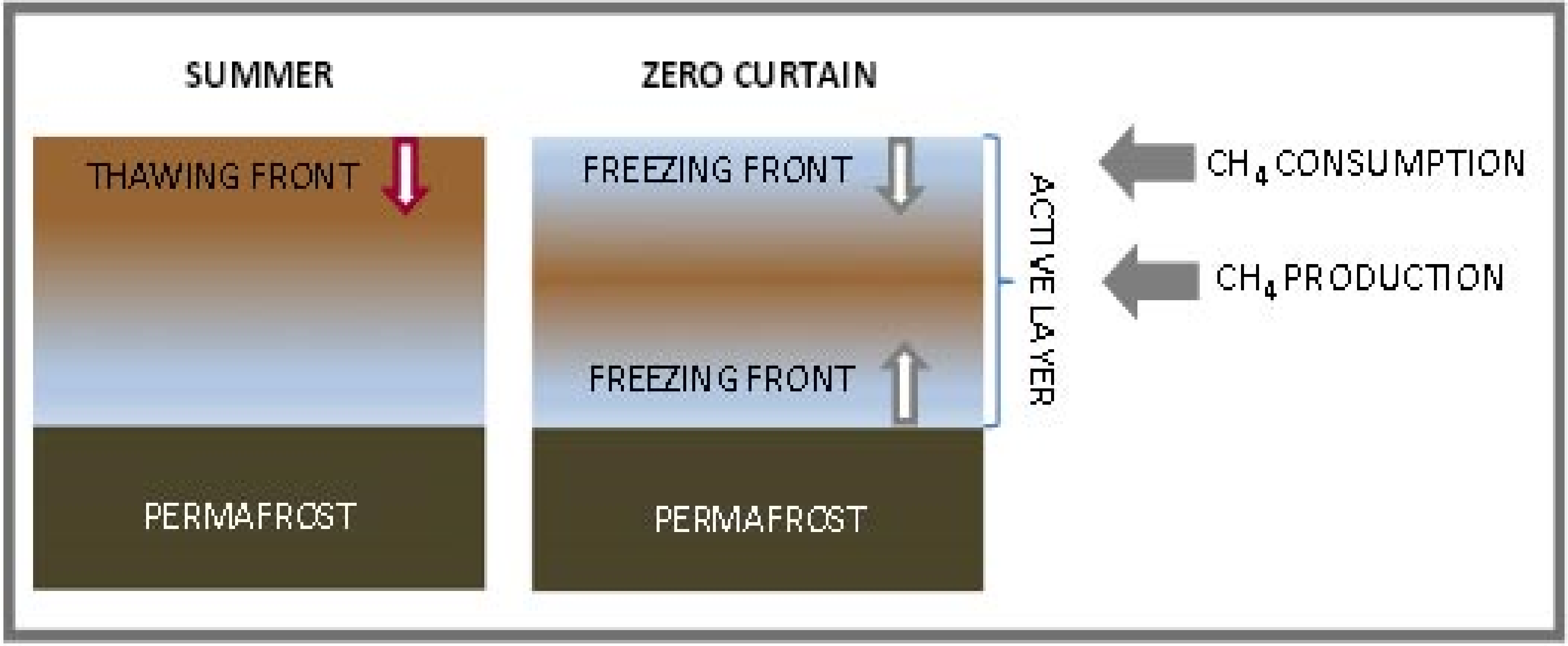



**Fig. 1.** Diagram of the hypothesized soil physical processes influencing $CH_4$ production and oxidation depending on the time of the season. We expect that during the zero curtain, the frozen near surface soil layer decreases $CH_4$ oxidation, resulting in substantial $CH_4$ emissions, even with lower $CH_4$ production. Light blue represents cooler soil temperatures, and light brown represents warmer soil temperatures; the arrows point in the direction of the thawing fronts in the summer and freezing front during the cold period.

**They find: Methane emissions do not end when the Arctic begins to re-freeze in September, but stay high thru December, and at lower level all Winter and Spring. This was unexpected. Not factored in to any climate models yet.**

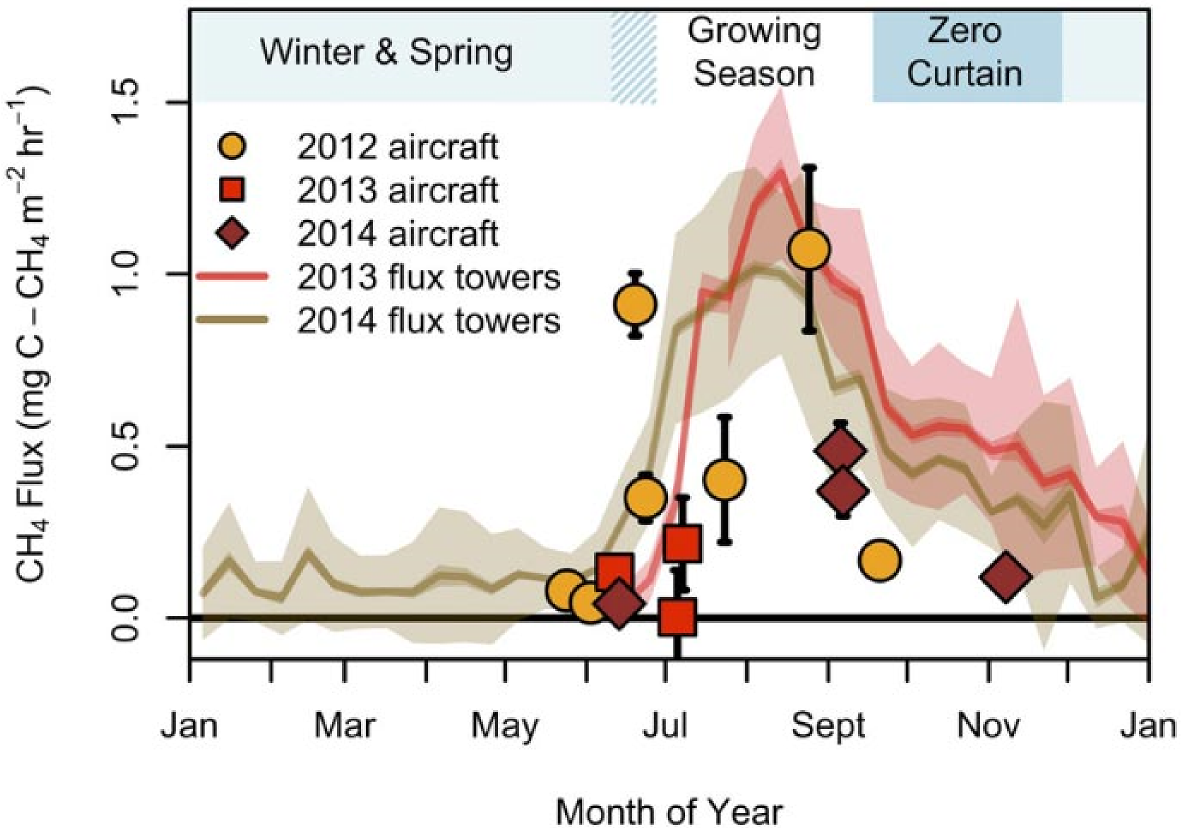



**Fig. 4.** Ten-day block average of the five EC flux towers over a 300-km transect across the North Slope of Alaska (shaded bands) for 2013 (red) and 2014 (brown), with the mean (solid line), 95% confidence intervals (darker shade), and SD in the $CH_4$ data (lightest shade). The regional fluxes of $CH_4$ calculated from the CARVE aircraft data for the North Slope of Alaska are shown for 2012 (yellow circles), 2013 (red squares), and 2014 (brown diamonds). The mean dates for the onset of winter, the growing season, and the zero curtain are indicated in the band on top. Regional scale fluxes of $CH_4$ (mg C-$CH_4$ $m^{-2}$ $h^{-1}$) showed similar seasonal pattern to the EC flux towers across multiple years.

# From the Conclusion section of [Zona *et al.* 2016]

- *"(We)…estimate 23±8 billion kg $CH_4$ per yr from Arctic tundra, similar to these previous estimates (ref 8, 32). Our estimated $CH_4$ cold-season emissions as well as those from inverse analysis (27, 32) are significantly higher than that estimated by land-surface models (27, 32). This difference was thought to be linked to anthropogenic emissions, because bio-genic emissions were assumed to be negligible during the cold season (27, 32). Overall, the seasonal patterns estimated by models (27) are very different from ours and generally do not include the substantial cold season $CH_4$ emissions found here. **Our finding of large cold-season biogenic emissions from tundra reconciles the atmospheric observations and inverse model estimates without the need to invoke a large pollution influence."***

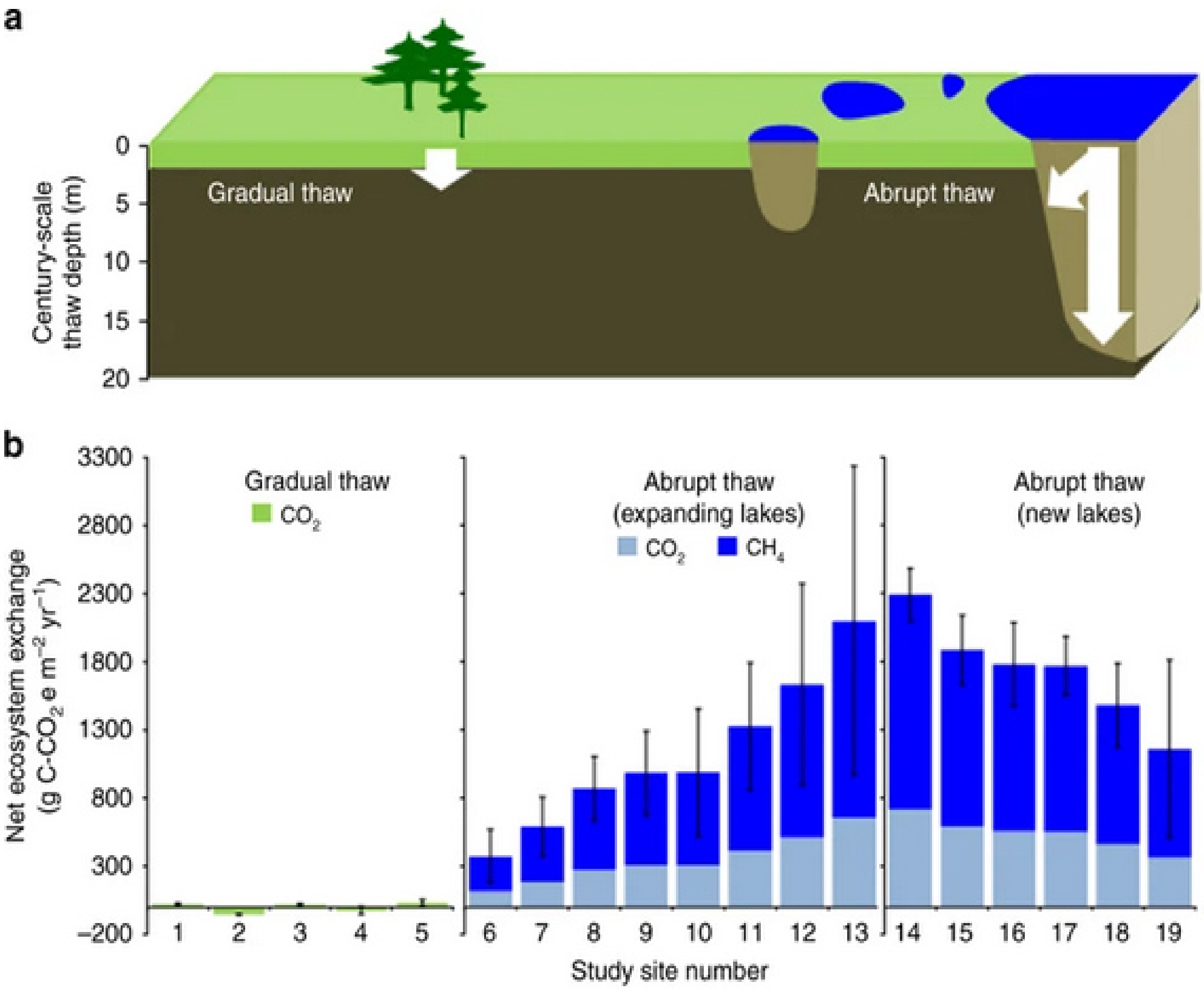
**IPCC Models Also Do Not Include**: trapped methane in frozen lakes, which is quickly released when the permafrost thaws. High pulse in first ~century (Katy Walter-Anthony's work)

# Dry vs. Wet sites Methane Contributions… (Zona *et. al.* )

- *"Continued warming and deeper snow are forecast for the future in the Arctic (33). Our results indicate these changes will result in globally significant increases in $CH_4$ emissions and that cold-season emissions will become increasingly important in this process.*
- *Additional year-round $CH_4$ fluxes and soil climate measurements at sites across the Arctic are urgently needed. Our results contradict model predictions that simulate and predict the largest $CH_4$ emissions from inundated landscape. <u>We showed that the largest $CH_4$ emissions are actually from the site with very low inundation</u>. We believe that the results of our study will impinge directly on our ability to predict future Arctic $CH_4$ budgets and allow us to revise the variables and processes that must be included to capture the true sensitivity of Arctic $CH_4$ emissions to climate change"*

# Methane (Hydrates) in the Permafrost – Global Climate Implications

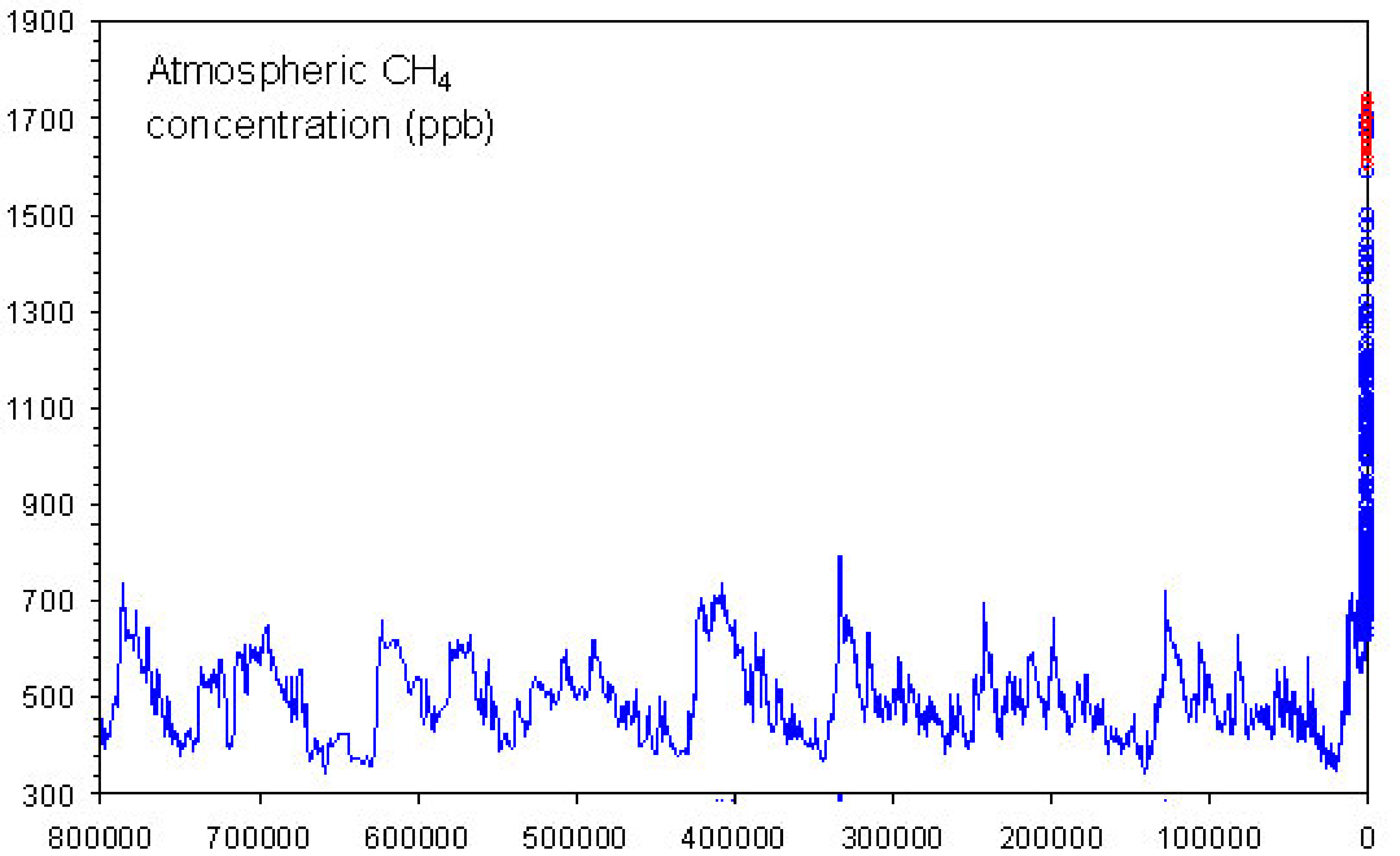
- The release of methane from the Arctic also contributes to global warming as a result of **polar amplification**. Alaska now has hot days even in March, as the resistant high pressure ridge predicted by Arctic Ocean thaw drives the polar jet stream north of much of Alaska.
- Recent observations in the Siberian Arctic show increased rates of methane release from the Arctic seabed.[source] Land-based permafrost, also in the Siberian arctic, was also recently observed to be releasing large amounts of methane, estimated at over 4 million tons – significantly above previous estimates.[source]
- Atmospheric methane levels are now at levels far above the regular peaks during past interglacial periods, and are over three times the pre-industrial levels.



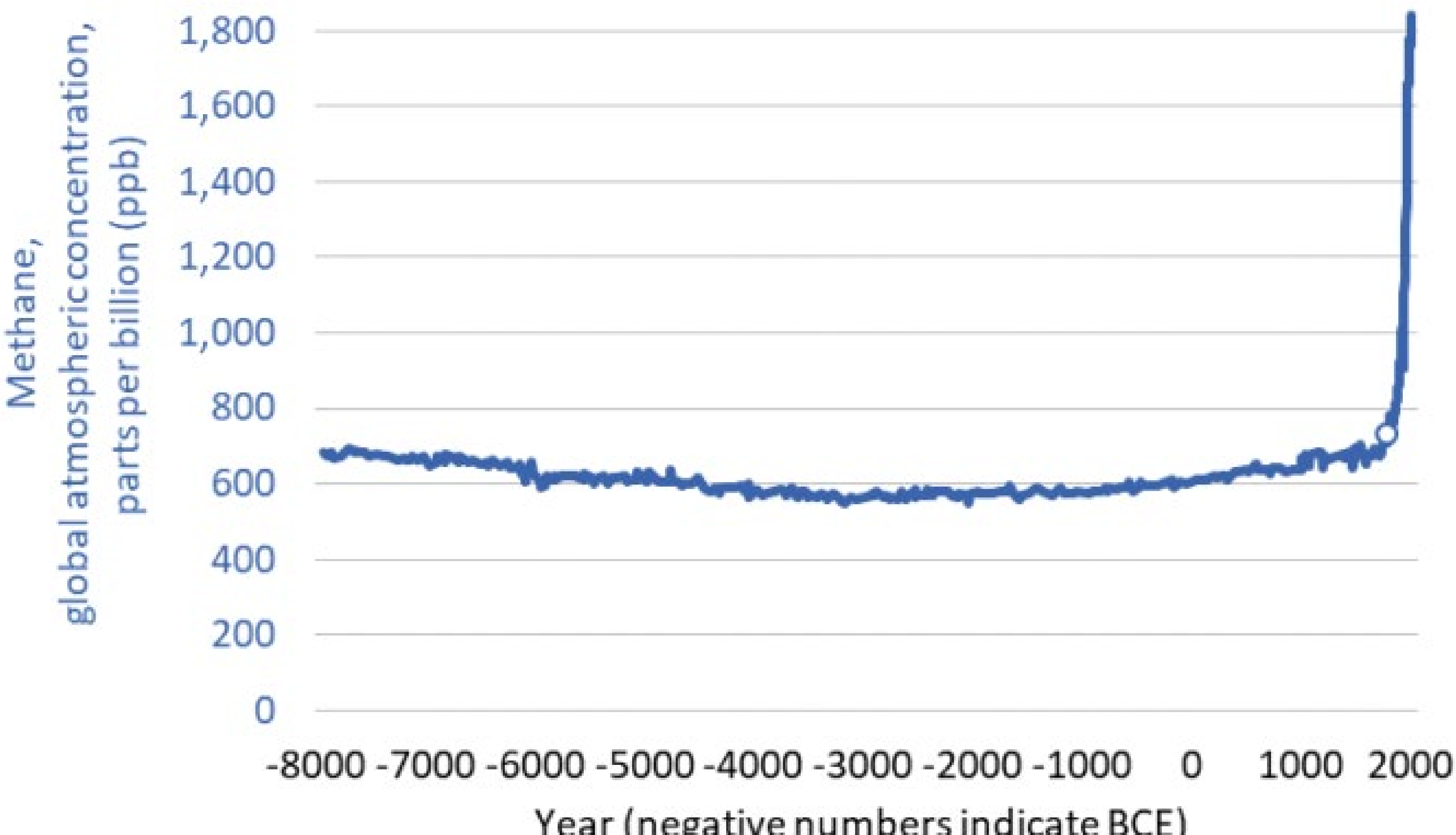

Conduction is very slow, resulting in very gradual thaw and very low rates of CO2e emission (green). By contrast, the thaw of ice on ground results in "thermokarst" lakes, which drives taliks, fluid heat transport, and "abrupt" (their words) CO2e release. Because the organic carbon is isolated from oxygen by being underwater, it instead emerges mostly - in climate forcing terms - as methane (dark blue).

Even future forecast studies which do include permafrost thaw (the IPCC AR5 did not) significantly underestimate emission rates. **Walter-Anthony *et al.* 2019** find dramatically higher CO2e emission rates (lower graph) when thermokarst lakes and their methane are included

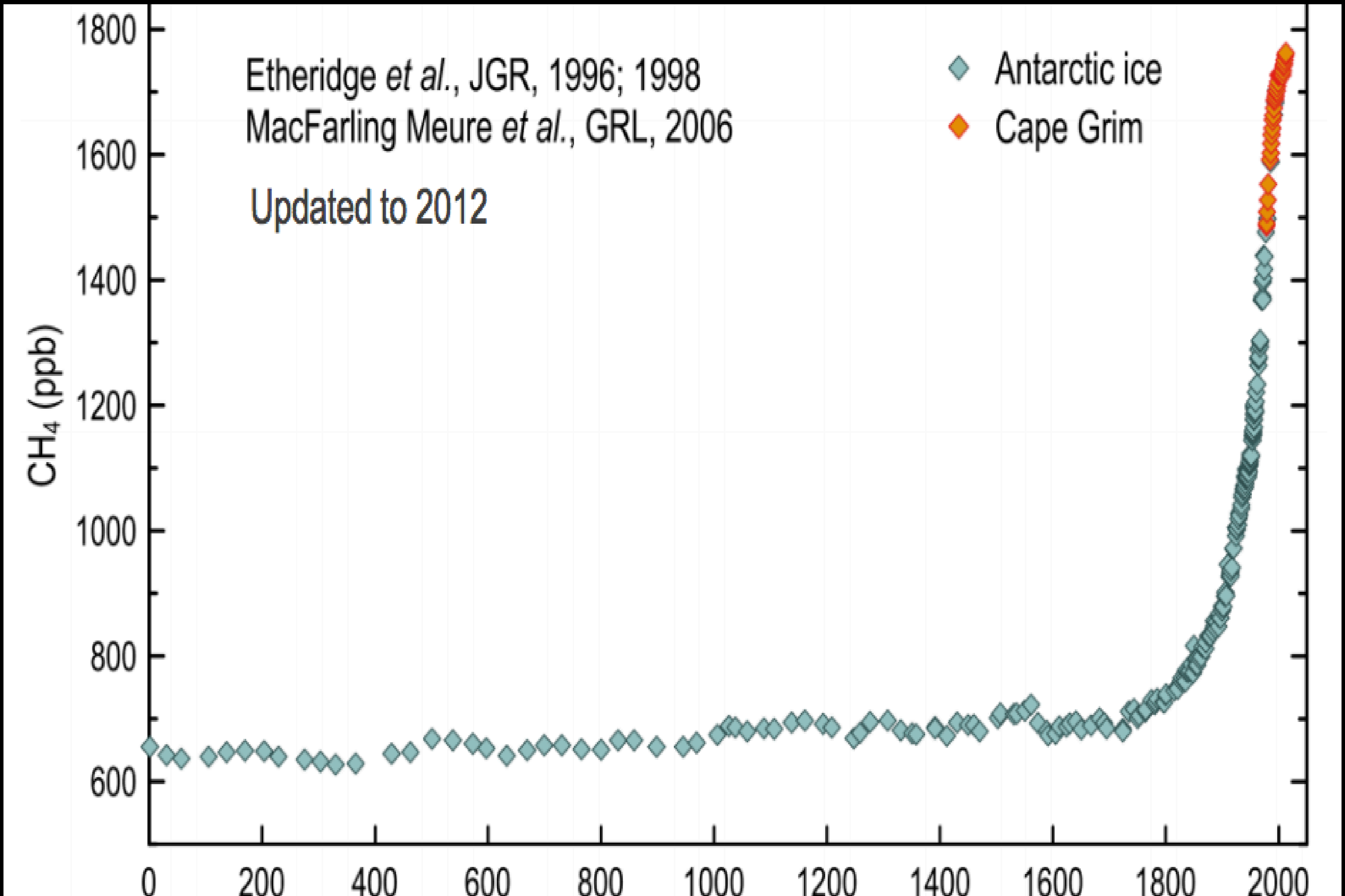
**While CO2 has risen 50% above Pre-Industrial, atmospheric methane has almost tripled, despite rapid oxidation (below, last 800,000 yrs)**



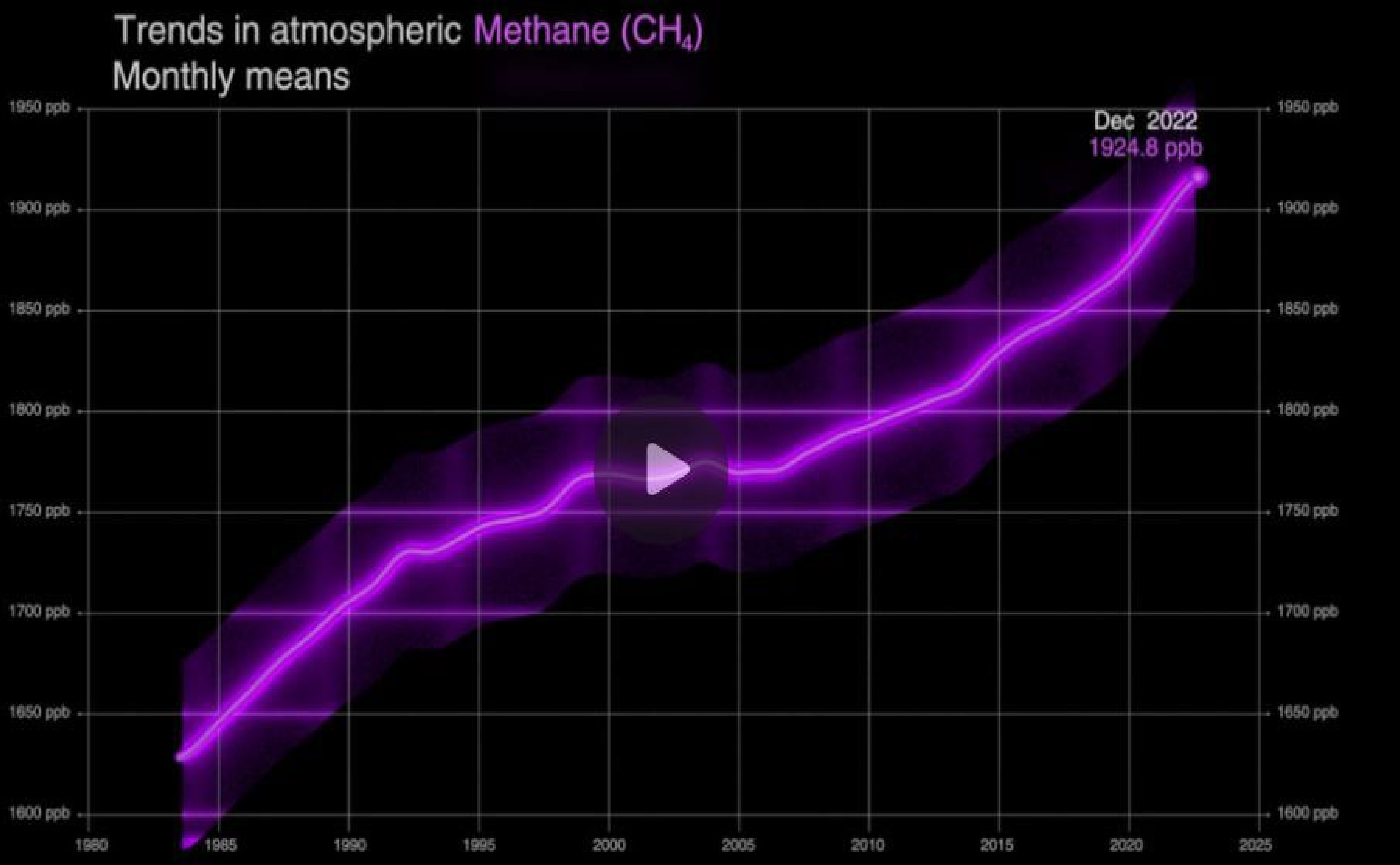
# Methane During the Holocene

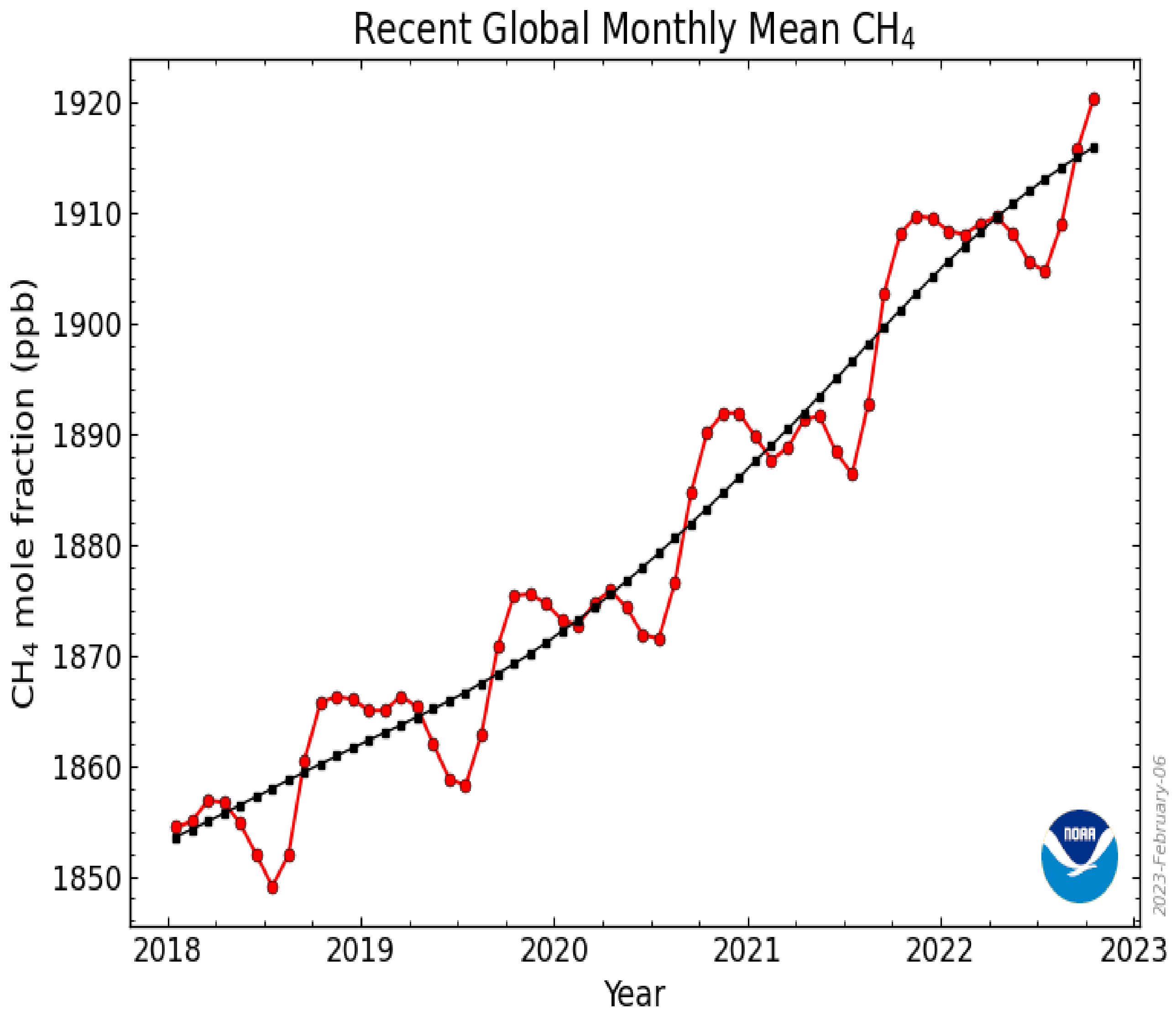


# Methane Levels: Stable for the Past Millennium – Until the Industrial Age



# Atmospheric methane up 16% in just the last 40 years, and re-accelerating in the past 15 years






**Recent acceleration believed due to reduced fossil fuel burning (NOx loss) and warming wetlands emissions, primarily.**

# IPCC scientists were instructed to assume that atmospheric methane levels would, starting in 2010, decline by 35% by 2050. They're not.

# Why the Decreasing Methane Rise Rate in the Late 1990's/early '00's?

- Slowing methane rise rate in 1990's is thought to be lowered methane loss from wetlands due to drought, with perhaps some contribution from the breakup of the Soviet Union and resulting (temporarily) lowered production of fossil fuels, (NOAA source).
- Droughts are expected to increase, yet wetland methane emissions are not predicted to continue to slow, because wetlands are now growing in the far north, as the permafrost now begins accelerated melting, responding to the large and accelerating loss of Arctic Ocean ice.
- Since methane oxidizes to CO2 with a half life of about 10 years, without methane release from fossil fuels and from other sources, methane levels would drop fairly quickly. See table on next page.
- However, the source/sink actual numbers vary somewhat between different studies by different authors (see IPCC 2007)
- **Large majority of methane emissions are human-caused**

# From Houweling *et.al.* 1999. The prior graph shows the imbalance has clearly accelerated since 1999

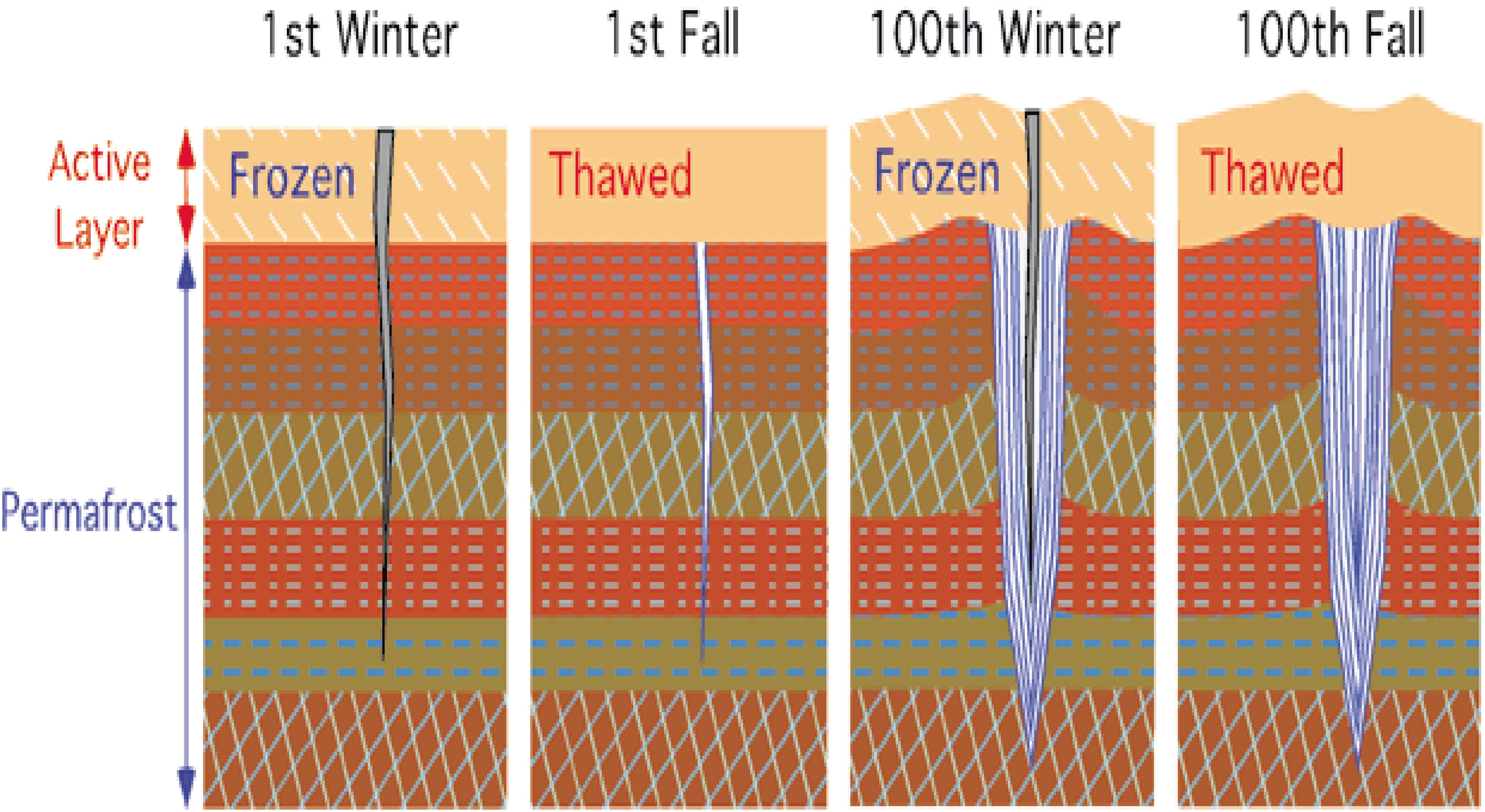
Houweling et al. (1999) give the following values for methane emissions (Tg/a=teragrams per y

| Origin | $CH_4$ Emission | | |
|---|---|---|---|
| | Mass (Tg/a) | Type (%/a) | Total (%/a) |
| **Natural Emissions** | | | |
| Wetlands (incl. Rice agriculture) | 225 | 83 | 37 |
| Termites | 20 | 7 | 3 |
| Ocean | 15 | 6 | 3 |
| Hydrates | 10 | 4 | 2 |
| Natural Total | 270 | 100 | 45 |
| **Anthropogenic Emissions** | | | |
| Energy | 110 | 33 | 18 |
| Landfills | 40 | 12 | 7 |
| Ruminants (Livestock) | 115 | 35 | 19 |
| Waste treatment | 25 | 8 | 4 |
| Biomass burning | 40 | 12 | 7 |
| Anthropogenic Total | 330 | 100 | 55 |
| **Sinks** | | | |
| Soils | -30 | -5 | -5 |
| Tropospheric OH | -510 | -88 | -85 |
| Stratospheric loss | -40 | -7 | -7 |
| Sink Total | -580 | -100 | -97 |
| **Emissions + Sinks** | | | |
| Imbalance (trend) | +20 | ~2.78 Tg/(nmol/mol) | +7.19 (nmol/mol)/a |

# Methane Clathrate Stability

- Current methane release has previously been estimated at 0.5 Million tons (Mt) per year.**[12]** Shakhova *et al.* (2008) estimate that not less than 1,400 Gt of carbon is presently locked up as methane and methane hydrates under the Arctic submarine permafrost, and 5-10% of that area is subject to puncturing by open taliks
- **In the very unlikely case that it would all enter our atmosphere at once, that would increase the methane content of the planet's atmosphere by a factor of twelve.[13]**
- **Wording note: "methane clathrate" = "methane hydrate" in our context**
- In 2008 the United States Department of Energy National Laboratory system**[14]** identified potential **clathrate destabilization in the Arctic as one the most serious scenarios for abrupt climate change, which have been singled out for priority research**. The U.S. Climate Change Science Program released a report in late December 2008 estimating the gravity of the risk of clathrate destabilization, alongside three other credible abrupt climate change scenarios.[15]
- **However, more recent work finds the risk of clathrate catastrophic (i.e. rapid) destabilization to be small, due to the depth, slow heat flow, and need for latent heat of fusion to be included before release can happen.**

# Taliks expand the area of unfrozen permafrost, over time, by exposing deep frozen permafrost to warmth



# Permafrost Carbon Flux


**Schaefer *et al.* (2011). Carbon released as $CH_4$ (methane), which converts to $CO_2$ + $H_2O$ over time. Because of this reaction, it is 25 times more powerful as GHG averaged over a century, but [72x more powerful when averaged over 20 years]. This means that if there is abrupt, large release of methane from destabilization, it is a far more powerful climate forcer than if released slowly over many decades. This study assumed human carbon emissions end in the year 2100. <u>Note that permafrost carbon flux remains amplifying (although decreasing) even after human carbon emissions are assumed to stop in 2100</u>**

# From Shaefer *et al.* (2011) - Conclusions Section Quoted Here…

***"The thaw and release of carbon currently frozen in permafrost will increase atmospheric CO2 concentrations and amplify surface warming to initiate a positive permafrost carbon feedback (PCF) on climate…. [Our] estimate may be low because it does not account for amplified surface warming due to the PCF itself…. We predict that the PCF will change the Arctic from a carbon sink to a source after the mid-2020s and is strong enough to cancel 42-88% of the total global land sink."***

**Recall from our Carbon Cycle lectures that land+ocean take up about half of human-caused CO2 emissions currently, so the the PCF is a big effect)**

***"The thaw and decay of permafrost carbon is irreversible and accounting for the permafrost carbon feedback will require larger reductions in fossil fuel emissions to reach a target atmospheric CO2 concentration."***

## (SvD 2012) found the Arctic loses ~all its carbon by 2300 (but newer studies suggest Arctic Lakes become a carbon sink after about a century of strong methane production

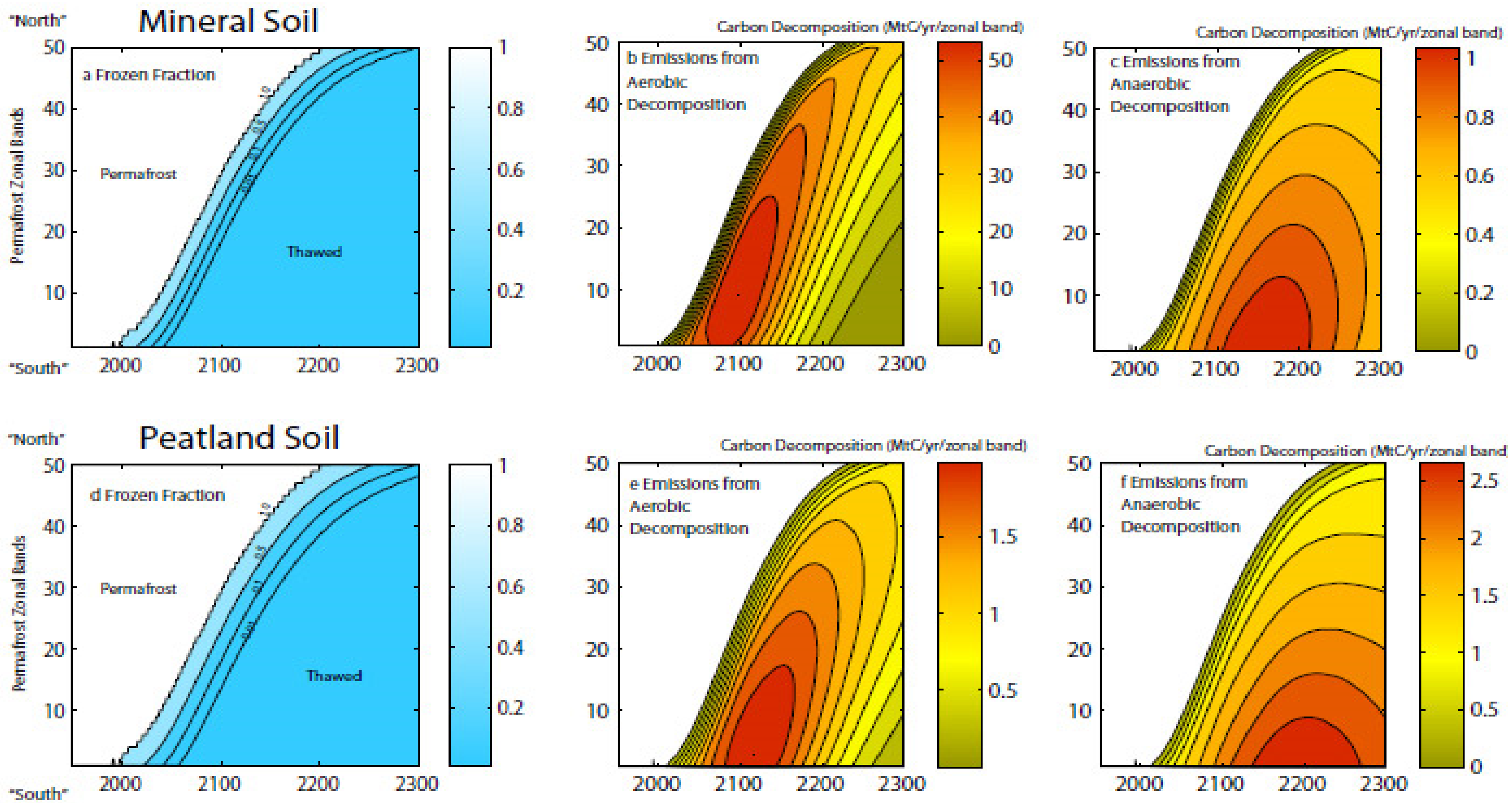



**Fig. 2.** Fraction of intact near-surface permafrost and carbon release in MtC $yr^{-1}$ per zonal band from mineral soil (upper row) and peatland soil (lower row) via aerobic (**b**, **e**) and anaerobic (**c**, **f**) decomposition, respectively, under the RCP8.5 scenario and illustrative default settings (see text and Table 2). Starting in the "Southernmos" zonal band, the thawing of the parameterized 3m thick soil layer progresses northward to colder zonal bands (vertical axis) over time (horizontal axis) (see **a**, **d**), being followed by carbon releases.

# 2,400 climate simulations of methane and CO2 release from thawing permafrost, and resulting global temperature probability bands (SvD 2012)

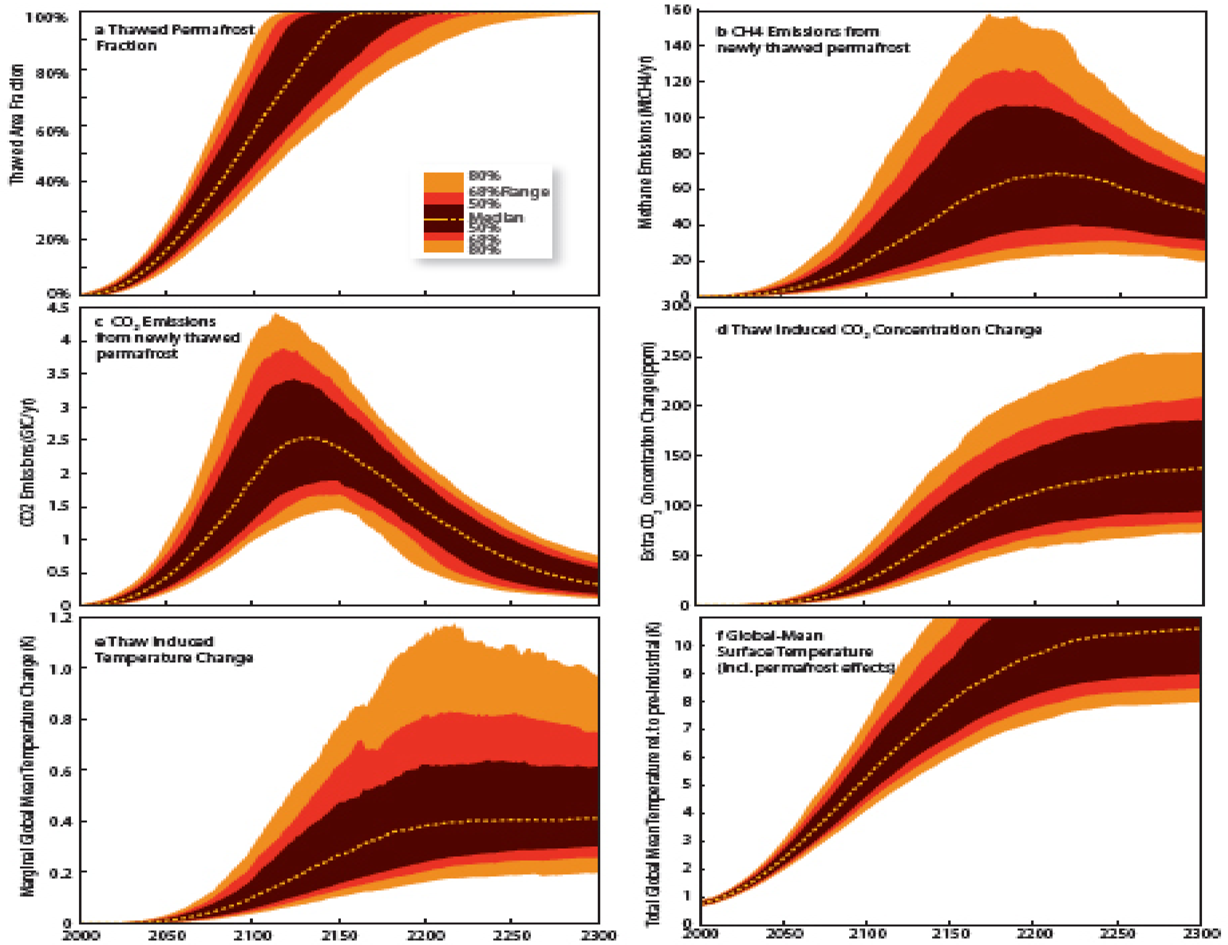



Fig. 3. This study's estimated ranges of thawed permafrost fraction (a), methane (b) and $CO_2$ emissions (c) from carbon in newly thawed permafrost soils, thaw induced $CO_2$ concentration (d) and temperature change (e), and the total anthropogenically induced global mean temperature anomaly (f). Results were obtained from an uncertainty analysis for the RCP8.5 scenario. The uncertainty ranges results from 2400 member ensemble simulations, using a Monte Carlo sampling that combines the joint distribution of 82 climate model parameters, 9 sets of 17 carbon cycle parameters and 22 independently sampled parameters of our permafrost model (see text and Table 1).

# Pathways of Permafrost Carbon Release

- **Wildfires**, increasing 200-560% by 2100, depending on RCP scenario, may be a strong underestimate, based on observations at lower latitudes
- **Coastline erosion** -> carbon release to ocean and atmosphere
- **Insects**
- **Direct soil, Arctic lake methane outgasing**
- **Soil structural failure**, releasing of deeper “thermo-karst” carbon
- All strongly temperature-dependent, and much higher for higher human CO2 emissions scenarios

**Tipping Point Passed?** New meta-study (Abbott *et al.* 2016): permafrost melt is now irreversible and the Arctic will become a carbon SOURCE soon, (Schuur *et al.* 2013), **regardless of emission scenario.** Increased uptake of carbon in biomass vegetation (green) will be overwhelmed by soil carbon release (brown). It will continue for at least a century. We remain on the RCP 8.5 track; *vs*. eco-friendly RCP 2.6 which includes strong active atmospheric CO2 removal

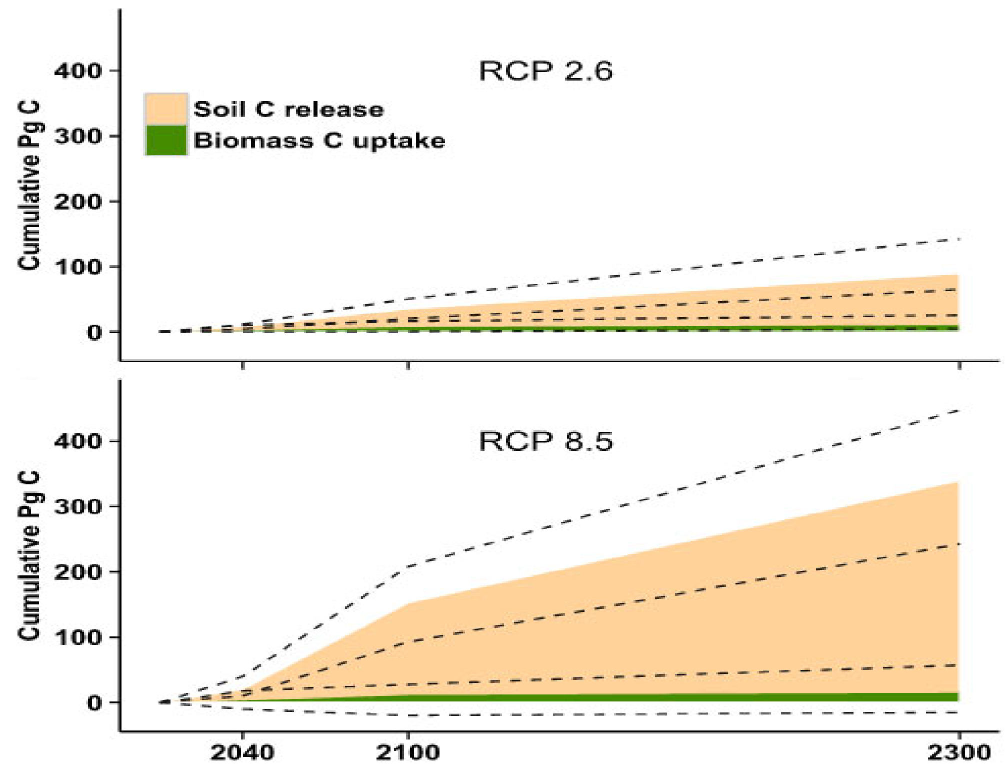



**Figure 4.** A comparison of soil carbon release recalculated from Schuur *et al* (2013) and non-soil biomass uptake in the permafrost region from this study for the business as usual scenario (RCP8.5) and the active reduction of human emissions scenario (RCP2.6). Polygons represent median cumulative change and dotted lines represent the interquartile range. Biomass carbon uptake is overlayed on soil carbon release to show the proportion of carbon release potentially offset by biomass. Linear rates of change were assumed between the three dates where estimates were provided.

# You may be wondering…

- So…the Arctic has been a carbon SINK?
- Yes; global warming-induced Arctic thaw supports increasing vegetation and trees.
- These take up atmospheric CO2 into biomass by photosynthesis
- But **Shaefer *et al.* 2011** find that even though this vegetation trend will continue, it will be overwhelmed by the mid 20’s by the **Permafrost Carbon Feedback.**
- <u>**Alas, as so often we’re seeing, it turns out even Shaefer *et al.* were too optimistic…**</u>

# Permafrost Melt as of 2017, is Already Overwhelming CO2 Uptake by Spreading Arctic Vegetation

- **Comane *et al.* 2017** discussed here, finds we've already crossed this line.
- Instead of the "mid 20's", the transition of the Arctic to being a CO2 source rather than sink, **already arrived in the mid 10's**.

## Early hope was that increasing vegetation in formerly frozen soil would sequester much of the carbon in thawing permafrost. Not so…

- The reason is that the thaw carbon release is strongly temperature-dependent, while the carbon uptake by new plants is not nearly so much.
- Permafrost thaw is predicted to continue for all IPCC emission scenarios, even the eco-friendly ones, and has little temperature dependence.
- **In other words, rising anthropogenic global warming causes sharply higher permafrost soil carbon <u>release</u>, while the amount additionally <u>sequestered</u> by northward migrating forests and shrubs, is tiny.**

# The IPCC had assumed the permafrost was not this vulnerable

- **Liljedahl *et al.* (2016)** find that ice wedge (talik) degradation causes drainage and subsidence changes which substantially worsens permafrost melt by providing heat pathways to deeper permafrost
- ***"The scientific community has had the assumption that this cold permafrost would be protected from climate warming, but we're showing here that the top of the permafrost, even if it's very cold, is very sensitive to these warming events,"*** Anna Liljedahl, the lead author of the study and a researcher at the University of Alaska in Fairbanks, told the **Washington Post**…

# Worse: Arctic Coastline Collapse Carbon Release

- **Tanski *et al.* (2019)** find that *"$CO_2$ was released as rapidly from thawing permafrost in seawater as it is from thawing permafrost on land."*
- The IPCC had simply assumed that carbon in coastal lands would go into the ocean and not the atmosphere… *"**Our results** question the paradigm in current **carbon budgets** that OC is entirely transported offshore, utilized for primary production or buried in shelf sediments (Bröder et al., 2016; Dunton et al., 2006; Vonk & Gustafsson, 2013).*

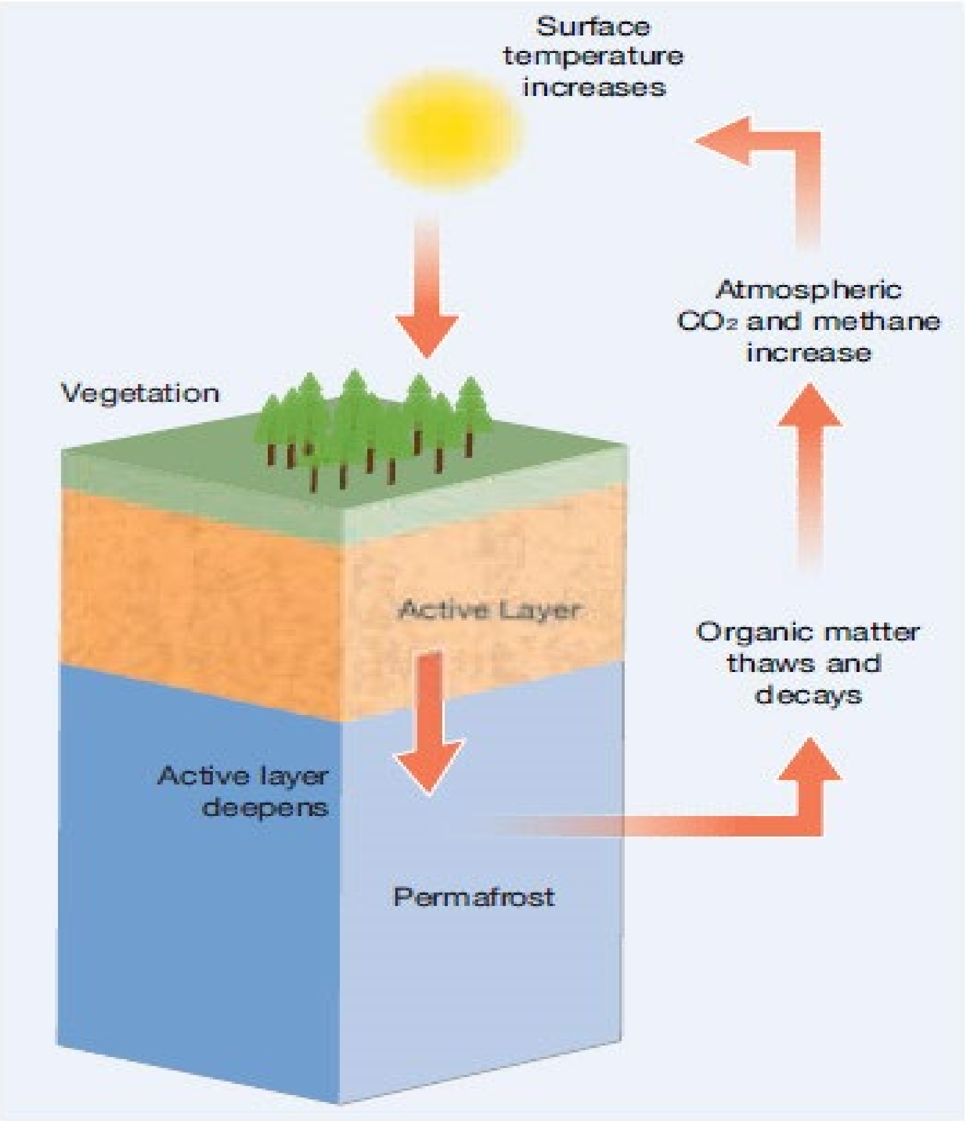



**Figure 21:** The permafrost carbon feedback is an amplification of surface warming due to the thaw of organic material currently frozen in permafrost, which will then decay and release $CO_2$ and methane into the atmosphere.

# What does carbon loss from the Permafrost mean for Global Temperatures ?

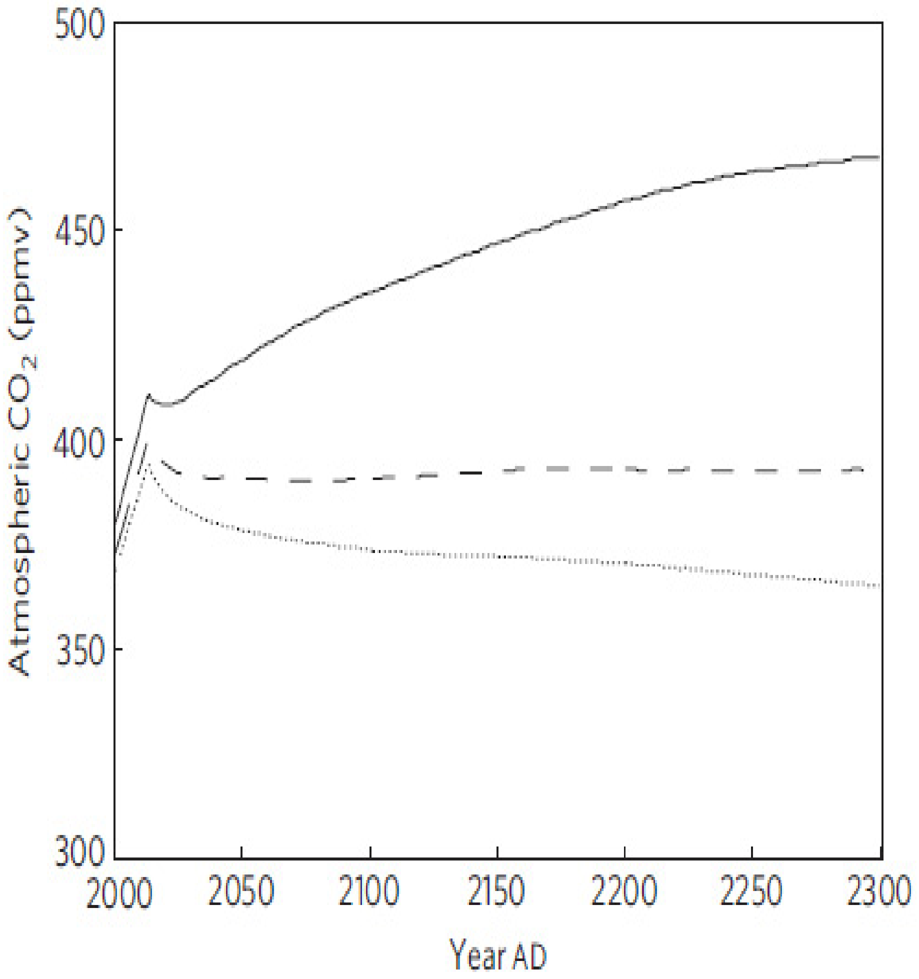



**Figure 3 | Evolution of atmospheric $CO_2$ concentration in response to a cessation of anthropogenic $CO_2$ and sulphate emissions in the year 2013.** The dotted line represents the response for a climate sensitivity (to a doubling of $CO_2$) of 2.0 °C, the dashed line a climate sensitivity of 3.0 °C and the solid line a climate sensitivity of 4.5 °C.

**For ECS of 4.5C (top curve), <u>even ending all anthropogenic CO2 and other GHG emissions in 2013</u>… still CO2 continues to rise, due to the permafrost carbon feedback ([MacDougall *et al.* 2012]), discussed [here]) initiating continued temperature rise for many centuries more.**

# But the Active Layer is Now Known to be Thinner.

- Newer work (**MacDougall and Knutti 2016**) finds the active zone (layer that freezes/thaws annually) in the permafrost is only 60% of that assumed in **MacDougall *et al.* 2012** work.
- That means faster conductive heat transport to the bottom of the active layer where permafrost frozen carbon can now be mobilized.

# Other Refinements…

- … their permafrost/climate model neglects methane, assumes all carbon emerges as $CO_2$, yet methane release from Arctic frozen lakes is already observed, as is subsurface permafrost methane.
- Indeed, **Shuur and Abbott** (2011) surveyed, found avg consensus that 2.3% of the carbon will emerge as methane; global warming forcing is ~120x higher than $CO_2$, pound for pound, at emission time.
- Methane will oxidize with a half life of about 12 years, so the forcing will be less than doubling initially seen.
- Alas, the 2016 work does not give ECS *vs*. $CO_2$ evolution, which would be so useful in combining with the new ECS work already described.

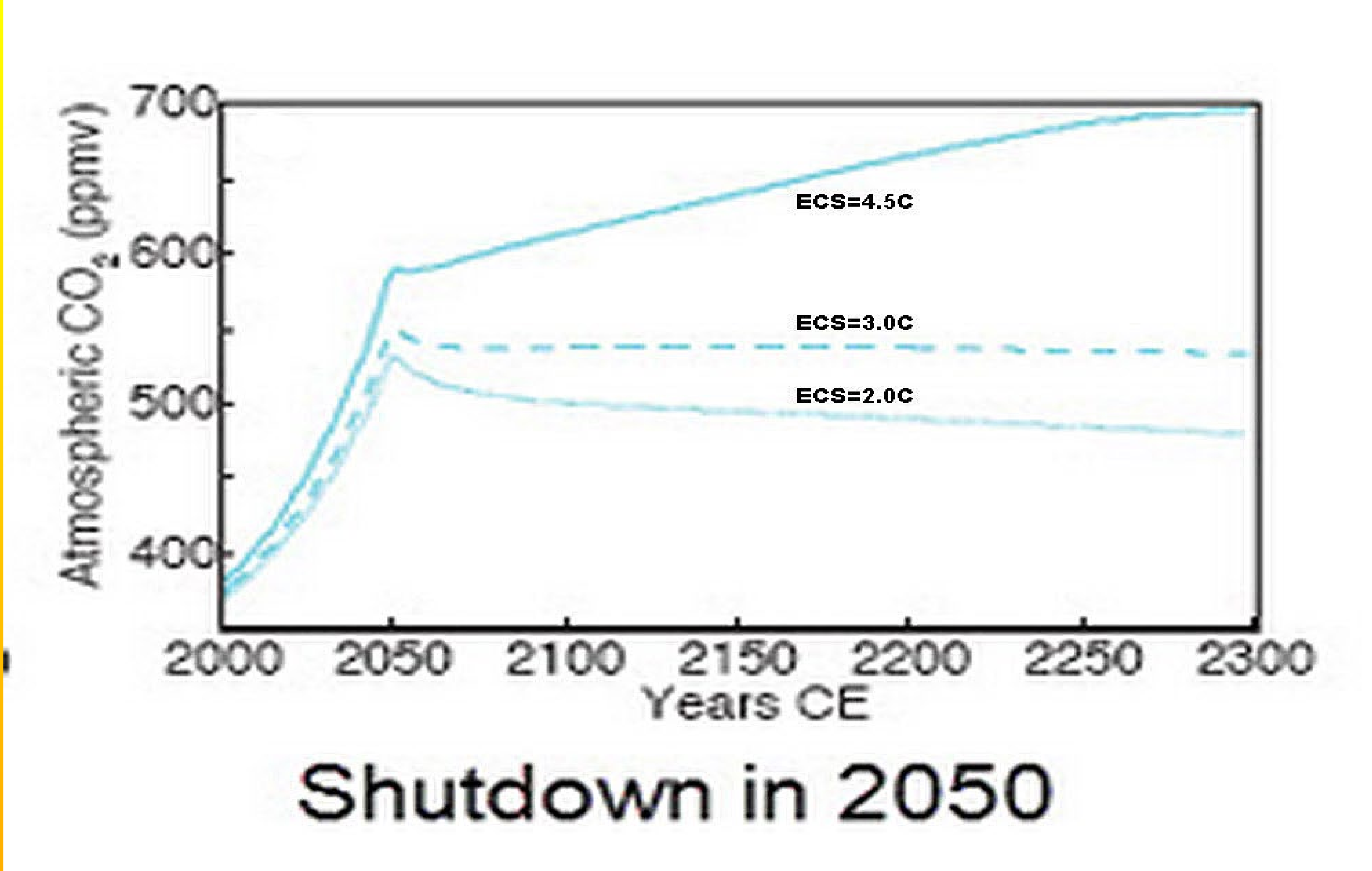
# The "Sustained Emission" GWP =SGWP, for Methane

- Whereas GWP is the global warming potential over time of a single emission. SGWP is far closer to real-world warming, and it's unrealistic for IPCC and the media to assume GWP numbers as if all non-CO2 GHG's will cease immediately.
- **SGWP numbers** are higher. Over a 70 year time horizon, methane is about 60% of what it was at emission time.

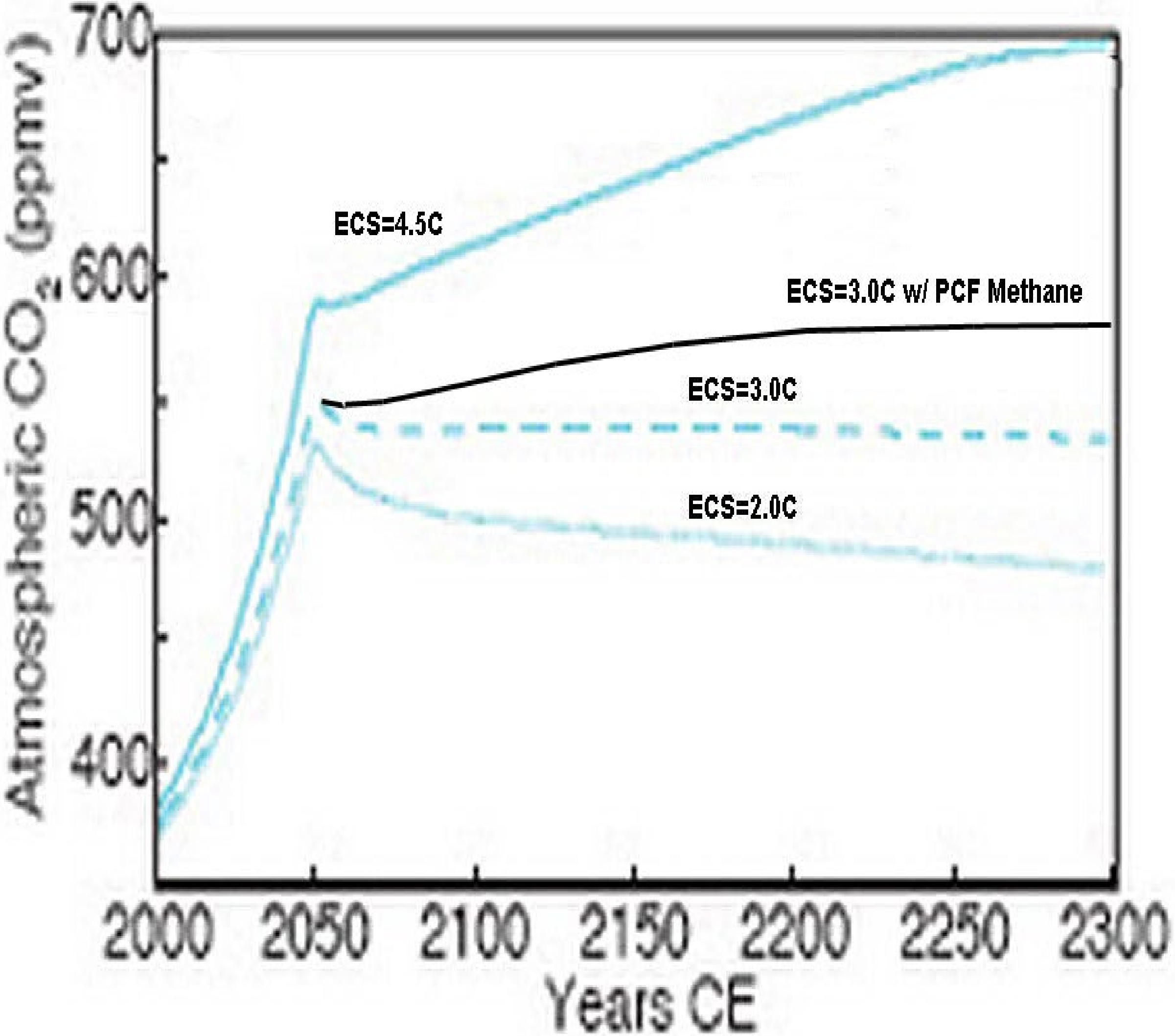
# For reference: Here's SGWP's for Methane from Neubauer and Megonigal (2015) Fig. 3 (read from their graph)

| Time (yrs) | sGWP (CH4) |
|---|---|
| 0 | 120 |
| 20 | 105 |
| 40 | 74 |
| 60 | 63 |
| 80 | 50 |
| 100 | 45 |
| 140 | 37 |
| 200 | 32 |
| 300 | 28 |
| 400 | 24 |
| 500 | 21 |

# And, what if we DON'T shut off carbon-based Civilization in 2013? (We didn't). What then?




Here's the MacDougall (2012) CO2 curves with assumed "Business as Usual" then complete human emissions shut down **in 2050** but again w/o Arctic (or temperature - dependent tropical) methane, nor revised active layer depth. **CO2 Much Worse: The ECS=3.0C case CO2 at shutdown is almost at 2x Pre-Industrial = 560 ppm. Now - add PCF Methane…**




Shutdown in 2050

**Here, adding in an estimated PCF methane curve as we did before; starting with the Solomon *et al.* 2009 curve, this time for CO2=550 ppm at shut down, revising active layer depth, and doing our same estimation technique to get CO2e global warming potential from 2.3% carbon as methane**

# To Summarize the Estimation Technique for Black Curves

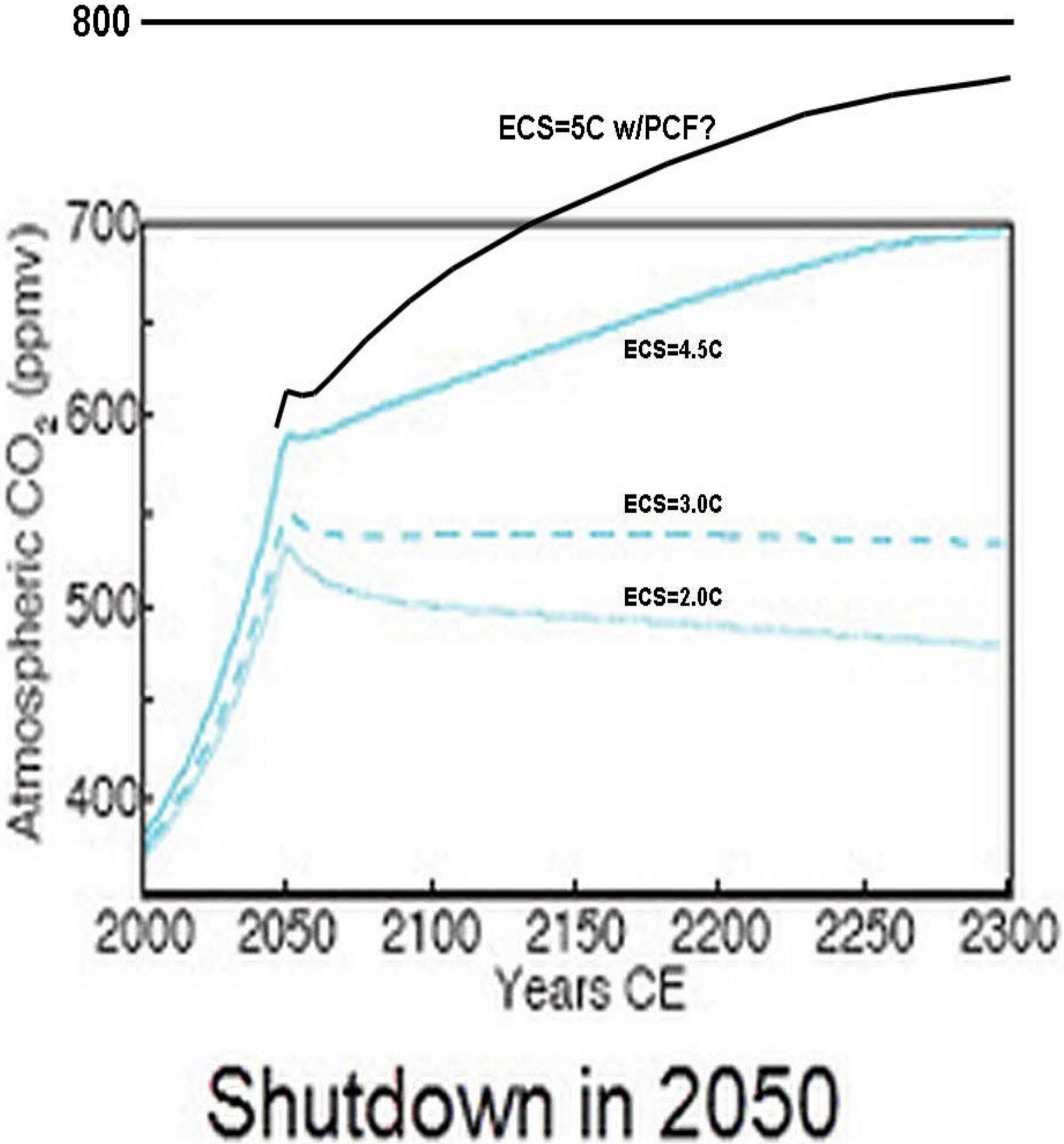
- The blue curves are MacDougall *et al.,* while the black curves are mine.
- I took the **difference** between the Solomon *et al.* 2009 post shut-down curve for 550ppm and the MacDougall curve for 550 ppm shutdown in 2050 as the PCF additional atmospheric CO2e contribution over time, after 2050.
- Increased the conductivity by 1/0.6 factor for the new thinner active layer.
- Then I took the resulting **difference** and multiplied it by 1.84 to account for the CO2e of MacDougall's neglected methane, which implies it comprises 45% of permafrost climate forcing initially but decaying over time. But SGWP for methane is 60% of initial over 70 year horizon.
- Since 1.84 x 0.6 =~1, then the delta from Solomon *et al.* to MacDougall is roughly correct, although my black curves should nominally be a bit higher near term and lower far term.
- I did this for ECS=3C which is what both Solomon and MacDougall assumed. Then I scaled up this difference for ECS=4.5C and for ECS=5C to match proportionally higher curves for these ECS's in MacDougall *et al.*
- *Still, this is only a very back-of-the-envelope estimate. A proper climate model should be used for better estimates.*

# It may still be too optimistic

- 580 ppm is a bit more than 2x pre-industrial, and so corresponds to a global temperature rise of about 3.1C of committed change.
- This is after continuing “Business as Usual” and then total shutdown of all human-generated GHG’s in 2050 and assuming ECS=3C.
- As the highly respected award-winning site “SkepticalScience”’s **summary** of the work says… ***“Unfortunately, there are several good reasons to consider the outlook in MacDougall et al. as rosy; as the authors themselves make clear.”***
- MacDougall *et al’s* results are only from triggered permafrost CO2 and methane alone (but missing thermo-karst methane, coastal/stream permafrost erosion (we just saw new work (**Tanski *et al.* 2019**) shows this is a strong carbon source, but neglected here and in following slides).

# One More CO2 Source Not Yet Included…

- As the AMOC slows, the ability of the oceans to distribute absorbed CO2 to the deep ocean also slows, increasing the "traffic jam" of surface CO2 and lessening the CO2 partial pressure gradient of the atmosphere into the ocean.
- This means the ocean's ability to absorb ~33% of our annual emitted CO2 will be reduced.
- I have not seen this quantified, yet.




**Now - if indeed ECS=5C going forward, as we saw recent studies indicate, then including permafrost methane drives atmospheric CO2e close to 770 ppm. corresponding to a global temperature rise of ~6.9C. And worse if we don't <u>end all human GHG emissions in 2050, just 30 years from now</u>**

# Katy Walter-Anthony *et al.* (2018) says even this is too optimistic

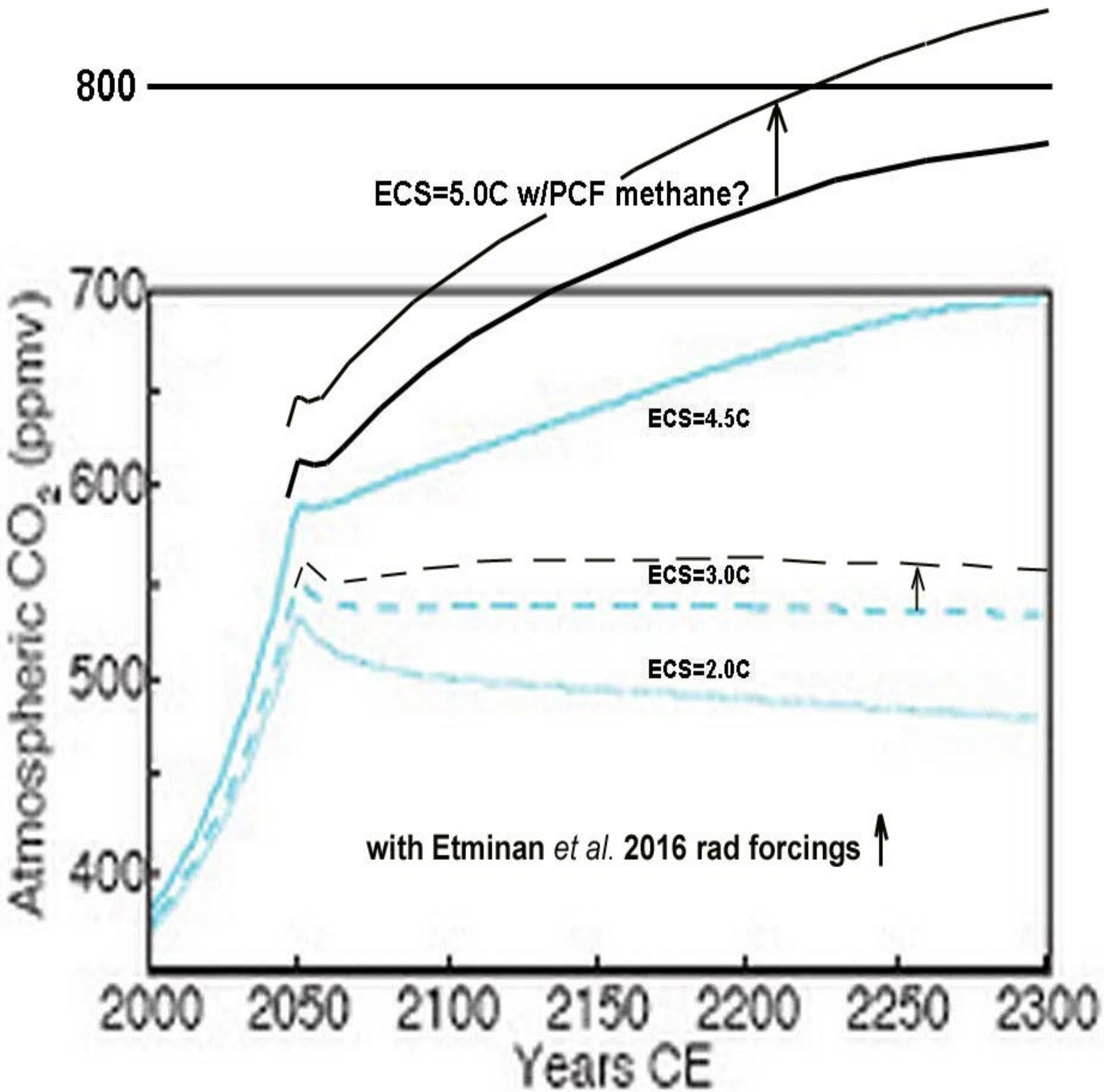
- Her team **finds that contrary to current** assumption that methane contributes only ~25% of permafrost thaw climate forcing (75% from $CO_2$), methane will actually provide **~300%** vs. $CO_2$ (!)
- Thermo-karst lake methane then comprises **~75%** of all permafrost climate forcing.
- My black curves, as described, only estimated **45%** for methane's contribution

# New research shows it is worse still. Etminan *et al.* 2016 recalculated the radiative forcings of methane and $N_2O$

- They included new data on short-wavelength absorption bands not included in the prior calculations like those used in the IPCC assessment reports syntheses.
- They showed that both of these GHG's have radiative forcings to climate that are about **23% higher than previously thought**.
- How would this affect those last curves?...

# Estimating the Resulting CO2e Trend

- From the **Etminan *et al.*** work, the methane half of the forcing then raises the curve about 11%
- From the Crowther *et al.* work, which did not include the higher forcing potential shown by **Etminan *et al.***, another 17% for a total of 30% higher.
- Let's be conservative and assume only **23%** rise, just to be sure we're not doing any double-counting here…




Shutdown in 2050

**I've merely added 23% onto the ECS=3C and ECS=5C curves, neglecting nonlinear amplifying and thermo-karst. Atmospheric CO2 is now driven to 840 ppm and beyond, by 2300. Temperatures would rise ~5Cx((840-280)/280) = +10C and beyond. <u>All, without any human fossil fuel use after 2050</u>**

# New Caveats

- Katy Walter-Anthony's work also finds that the methane emissions, while worse than previously thought, max out sooner, and thermokarst lakes after a century or so should instead become carbon sinks as photosynthesis rises and methane producers decline.
- Better curves would likely peak higher and sooner and then decline, rather than the gradual rise shown. That's not good, for civilization.
- And… this is a very active area of research and numbers are uncertain as the physics and the landscape are both complex.

# And: IPCC Models Do Not Include: Soil Carbon Loss from Warming Soils

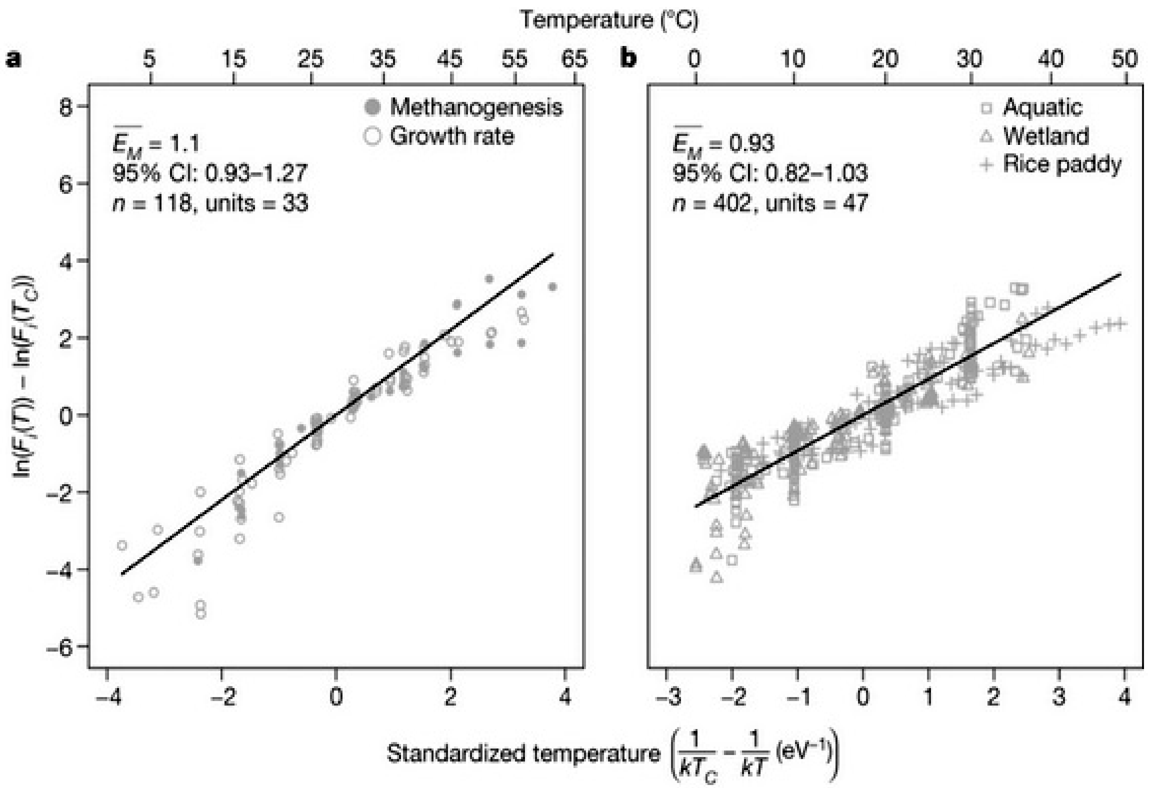
- **Crowther *et al.* 2016** show that this feedback alone will **raise CO2 emissions rates by 17%** - as much as the entire U.S. contributes to global CO2. (Lead author **interview**, and discussion)
- IPCC Earth System Models instead optimistically assumed the “greening of the Arctic” would sequester carbon. But detailed studies show that will be overwhelmed by the increased metabolism of soil microbes which release CO2.
- **IPCC AR5 models did not include this feedback. To be more honest, they set it =0.**

# "Incompatible with an Organized Society"

- Yet, as Prof. Kevin Anderson summarizes, even just … **"*a +4 degrees C future is incompatible with an organized global community, is likely to be beyond 'adaptation', is devastating to the majority of ecosystems, and has a high probability of not being stable*."** (meaning, it continues hotter).
- Think this is doomsday poppycock? Nobel physicist and former Secretary of Energy under Obama – Steven Chu – entirely independently, finds it **highly likely** that we'll exceed 550-600ppm CO2 equivalent.
- **The course we're on is sheer madness**.

# Not Included – New Work on the Strong Temperature Dependence of Methane Emissions in Global Wetlands

# Yvon-Durocher *et al.* 2014 find a 44:1 amplification of methane emission rates with temperature, across all ecosystems large and small. +1C raises methane emission rates 15%

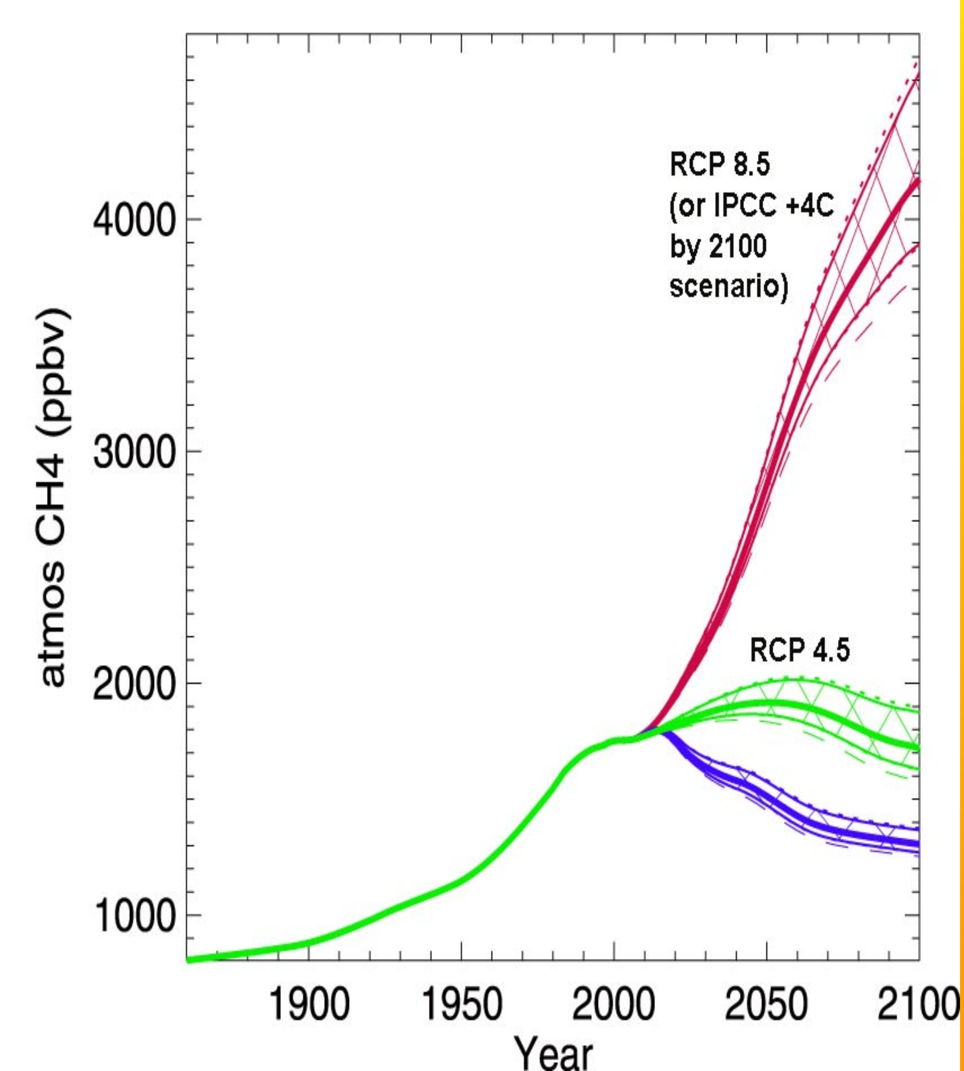



Caption

Figure 1: Temperature dependence of CH4 production and related processes at population and community levels. Temperature dependencies for methanogen populations in culture (a) and anaerobic microbial communities from natural sediment samples (b) are separately characterized using mixed-effects models by fitting Boltzmann-Arrhenius functions with experimental-unit-level random effects on the apparent activation energy and rate at fixed... +

**0** Recommendations

# Methane emissions from complex natural systems remain difficult to predict with the desired precision. But here's the latest




Gedny *et al.* (2019) find, on the temperature trajectory RCP 8.5 (nominally +4C by 2100 in the IPCC), that methane atmospheric concentrations from non-polar wetlands rise strongly, rising to over 4,000 ppb from today's 1850 ppb

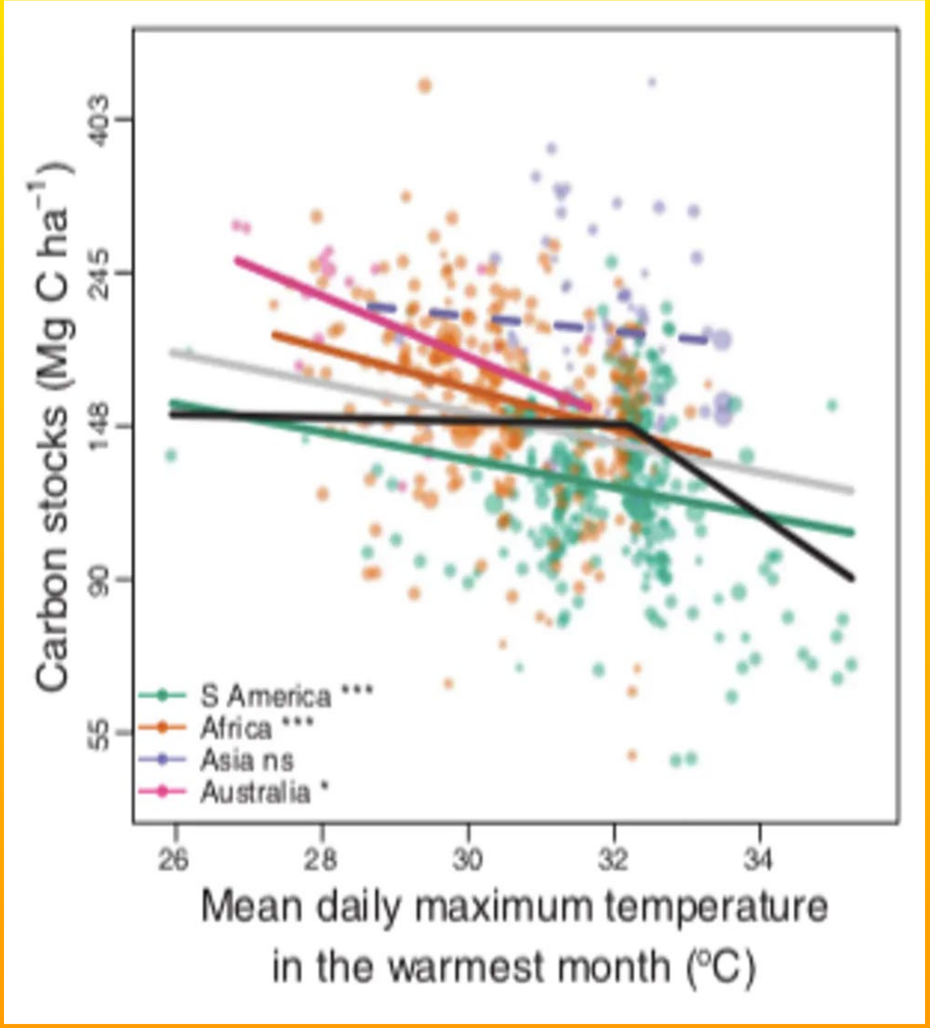
# More Bad News – Trees are Turning Against Us

- In a warming, drying land, plants use water more efficiently, narrowing their stomata, where CO2 and water vapor transpire.
- This appears to impair local evaporative cooling more than we had thought (**Park *et al.* 2020**)

# This means less evaporative cooling, and is a strong effect. Existing cooling by plants will drop as $CO_2$ levels rise

- This **Scientific American article** discusses the new research
- This effect has only recently been studied, but **Park *et al.* 2020** find it accounts for 10% of the warming in the Arctic, and as much as an additional 28% of warming in lower Northern Hemisphere latitudes.
- This is very new, with significant uncertainties. It is not incorporated into existing climate models, let alone the over-mild AR5 models the policy people love to quote. It will worsen future predictions.

# Worse: A New Tipping Point at 90F in Tropical Forests' Warmest Months




- **Sullivan *et al.* 2020** (behind paywall but discussed **here**) find that at this temperature, tropical rainforests transition to a state of **steep carbon loss**, as tree growth is stunted and decay amplifies.
- **They point out this corresponds to a global temperature rise of +2C, which, as we saw, is virtually impossible to avoid.**
- And, clearly a dead tree will give even less evaporative cooling for climate

## Even earthworms are turning on us; Non-native earthworms are invading the North American boreal forest

- They feed exclusively in the shallow leaf litter, thus releasing carbon directly to the atmosphere.
- Cameron *et al.* 2015 find these worms alone will turn **50-94% of the boreal forest floor carbon into atmospheric CO2 in the next century**, with most damage happening in the first ~37 years.
- This has not been included in any climate models as of 2021.

# [Lubbers *et al.* 2013 ]find that earthworms' net effect, even after improving soil quality, is to <u>increase</u> CO2 emissions.

- Cameron and Bayne (2009) find that these worms are already occupying 10% of Alberta's northern boreal forest, and would occupy 50% by 2060.
- They are found right up to the receding edge of the permafrost (Shaw, discussed here)

The world's boreal forests have been largely earthworm-free since the last Ice Age. But as invaders arrive and burrow into the leaf litter, they free up carbon and may accelerate climate change. Cristina Gonzalez Sevilleja

# At CO2e over 800 ppm, fine-tuning the details would be unlikely to avoid a catastrophic scenario

- … since societal breakdown would almost certainly be underway, and the remaining population could not function in a way recognizable today.
- It would be a different planet. High tech science and engineering to deal with climate would likely be difficult if not impossible. We instead would be forced to focus on lower level concerns. The “Great Simplification” as some delicately term it.
- Other physics would likely have added further trouble. Soil carbon would be net outgassing as well, ocean CO2 absorption would be strongly negatively affected by the widespread death of aragonite species from both ocean heat, stagnant anoxic conditions, AMOC shutdown, and rising acidity.

# Dr. Peter Ward worries that global ocean thermo-haline circulation (THC) shutdown could initiate a hydrogen sulfide-induced mass extinction…

- …as has possibly happened several times in Earth's past when massive volcanism produced large CO2 outgassing.
- On the reassuring side, THC shutdown happened in the Eemian interglacial w/o this disaster. It may require much higher forcing and duration than past interglacials like the Eemian could provide.

- One aspect is clear and unambiguous, and that is that permafrost carbon release continues for many centuries after the end of anthropogenic GHG release, once permafrost thaw is initiated.
- The work of Vaks *et al.* 2013 on paleo data, together with the permafrost melt we're observing, suggests that **we are crossing that tipping point right now.**
- **Then, there's another surprise that might be waiting…**

# And…The "Compost Bomb Instability"

- This is an instability discovered by Jenkinson (1991) and explored by **Luke and Cox 2011**, and **Wieczorek *et al.* (2010)**
- *"…we have shown here that there is a general class of dynamical systems, including the climate-carbon cycle model (1.1)–(1.3), which define a dangerous **rate** rather than a dangerous **level** per se. We suspect that such rate-dependent tipping points are much more common in the climate system than is typically assumed, and suggest that deriving the associated critical rates of global warming, as we have done here for the 'compost-bomb instability', would provide valuable guidance for climate change policy."*

# Warming conditions cause soil carbon to escape to the atmosphere

- If the heat generated does not escape fast enough in order to damp combustion, then run-away combustion and $CO_2$ release happens catastrophically.
- **Luke and Cox (2011)** find that for the vast peat areas of the Earth, including in the Arctic, **the critical warming rate is 0.088C per year**
- Warming rates faster than this trigger the "**Compost Bomb Instability**", with serious climate consequences.
- New work; **Clark *et al.* 2020**

PROCEEDINGS OF THE ROYAL SOCIETY A

*Proc. R. Soc. A* (2011) **467**, 1243–1269
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*Published online* 24 November 2010

# Excitability in ramped systems: the compost-bomb instability

BY S. WIECZOREK*, P. ASHWIN, C. M. LUKE AND P. M. COX

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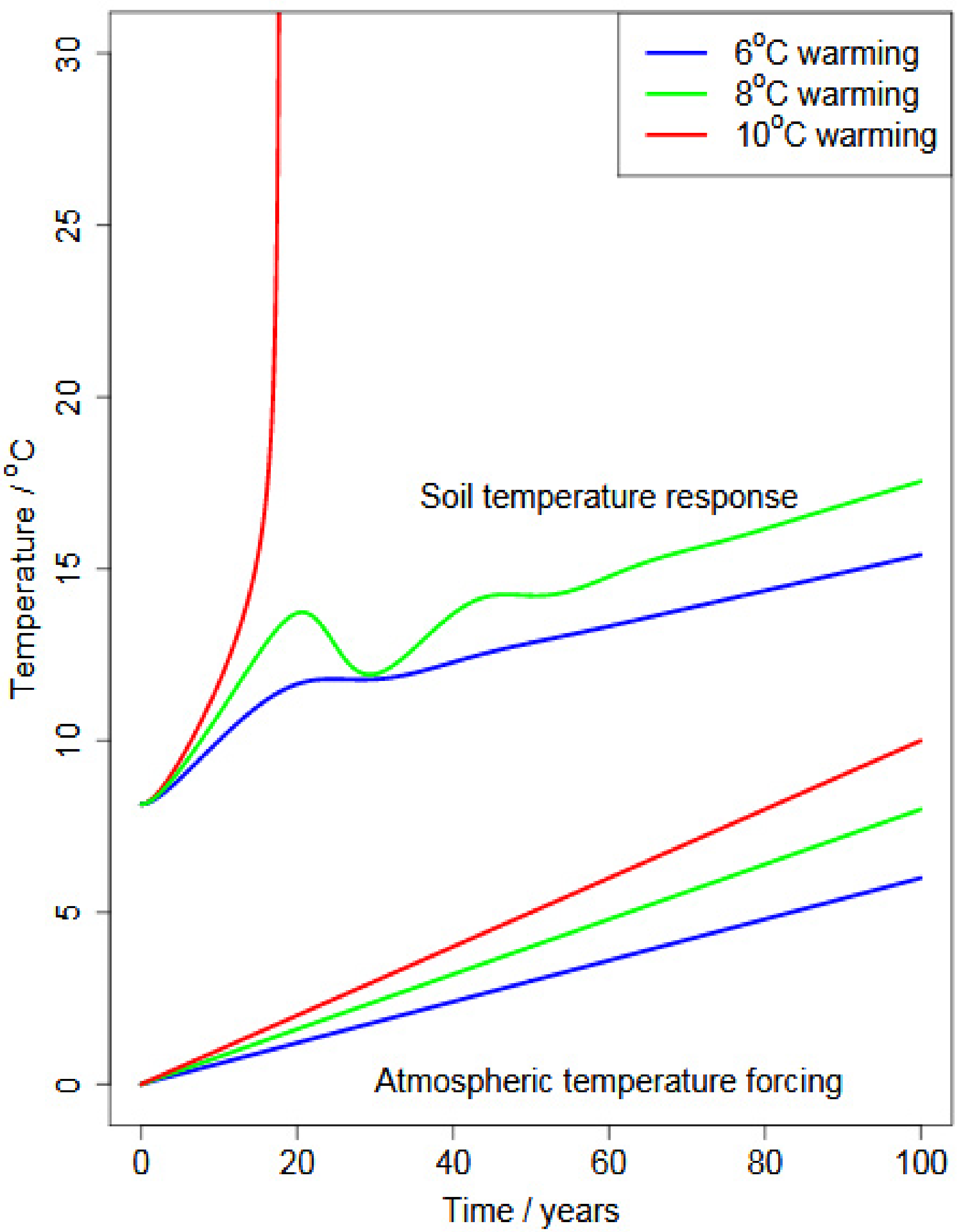
The paper studies a novel excitability type where a large excitable response appears when a system's parameter is varied gradually, or ramped, above some critical rate. This occurs even though there is a (unique) stable quiescent state for any fixed setting of the ramped parameter. We give a necessary and a sufficient condition for the existence of a critical ramping rate in a general class of slow–fast systems with folded slow (critical) manifold. Additionally, we derive an analytical condition for the critical rate by relating the excitability threshold to a canard trajectory through a folded saddle singularity. The general framework is used to explain a potential climate tipping point termed the 'compost-bomb instability'—an explosive release of soil carbon from peatlands into the atmosphere occurs above some critical rate of global warming even though there is a unique asymptotically stable soil carbon equilibrium for any fixed atmospheric temperature.

**Keywords: excitability; singular perturbation theory; climate tipping points; soil carbon; folded saddle; non-autonomous systems**

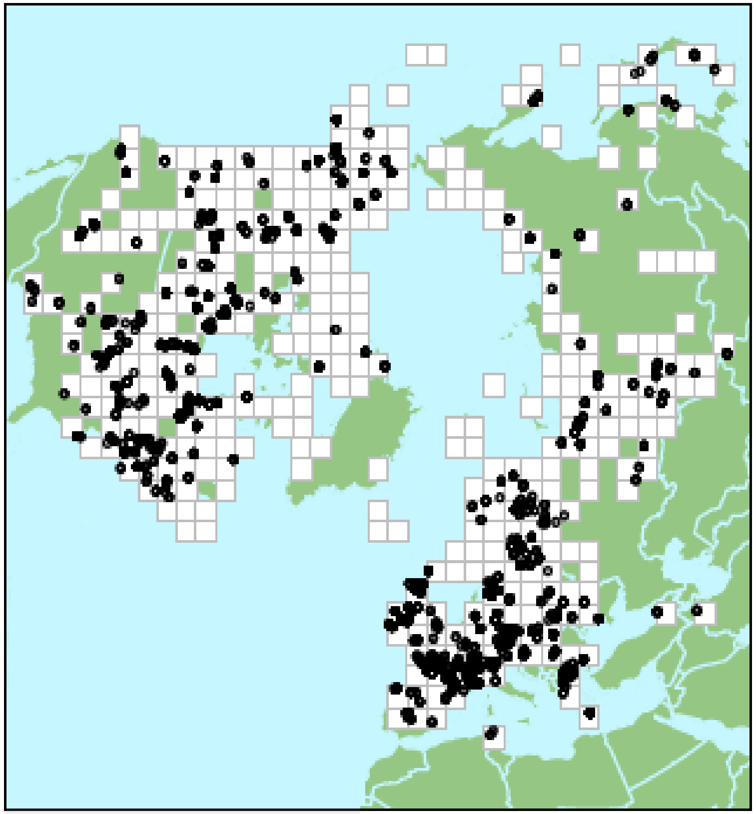



**When the atmospheric temperature rise rate exceeds 0.88C per decade, then within 15 years soil carbon in buried peat ignites, setting off the <u>"Compost Bomb"</u> and catastrophic carbon release to the atmosphere**

***"An explosive release of soil carbon from peat-lands into the atmosphere occurs above a critical rate of global warming, even though there is a unique asymptotically stable soil carbon equilibrium for any fixed atmospheric temperature"***

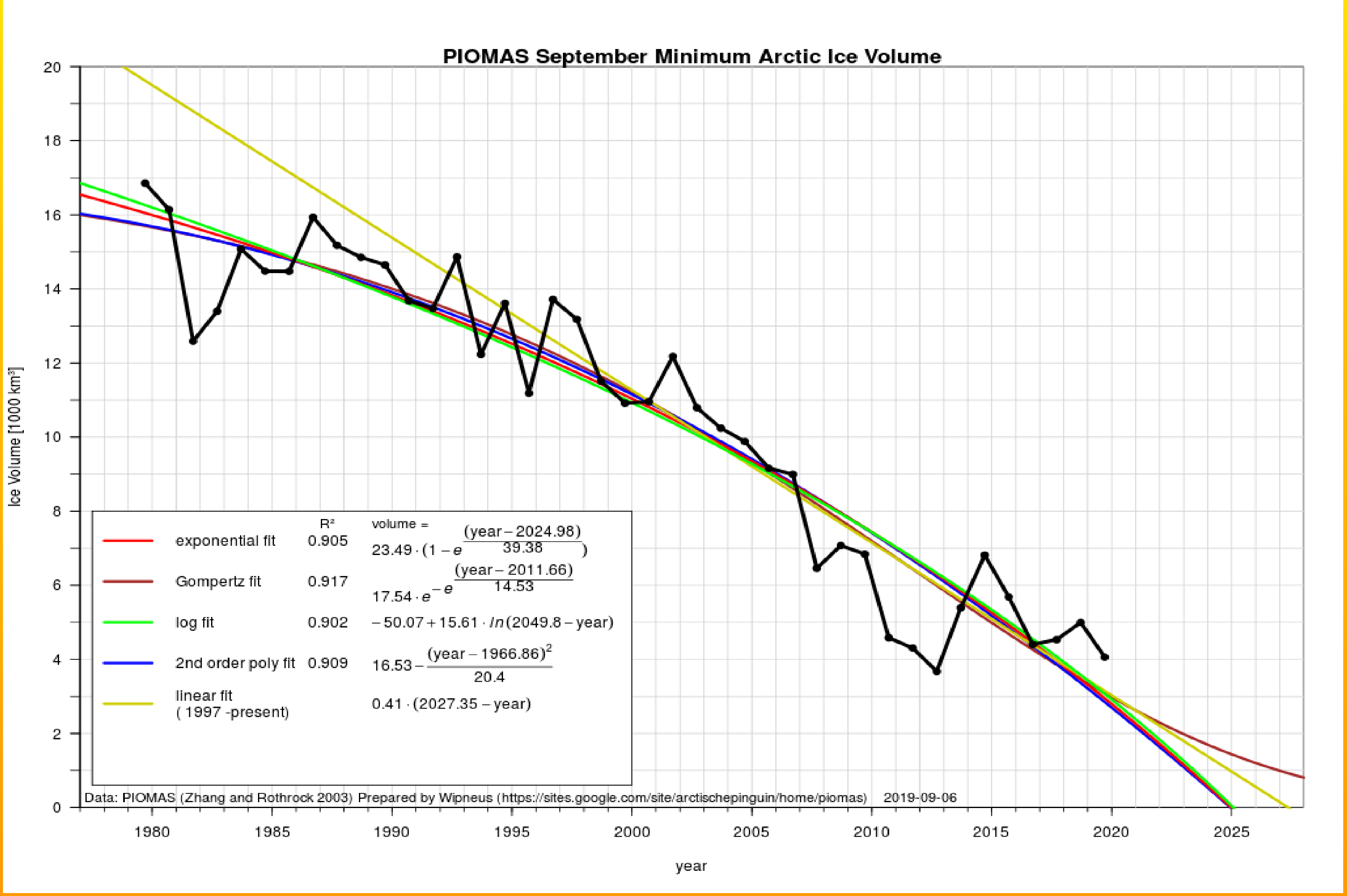
**(Wieczorak *et al.* 2010)**

# So, How Much Peat Carbon is There?

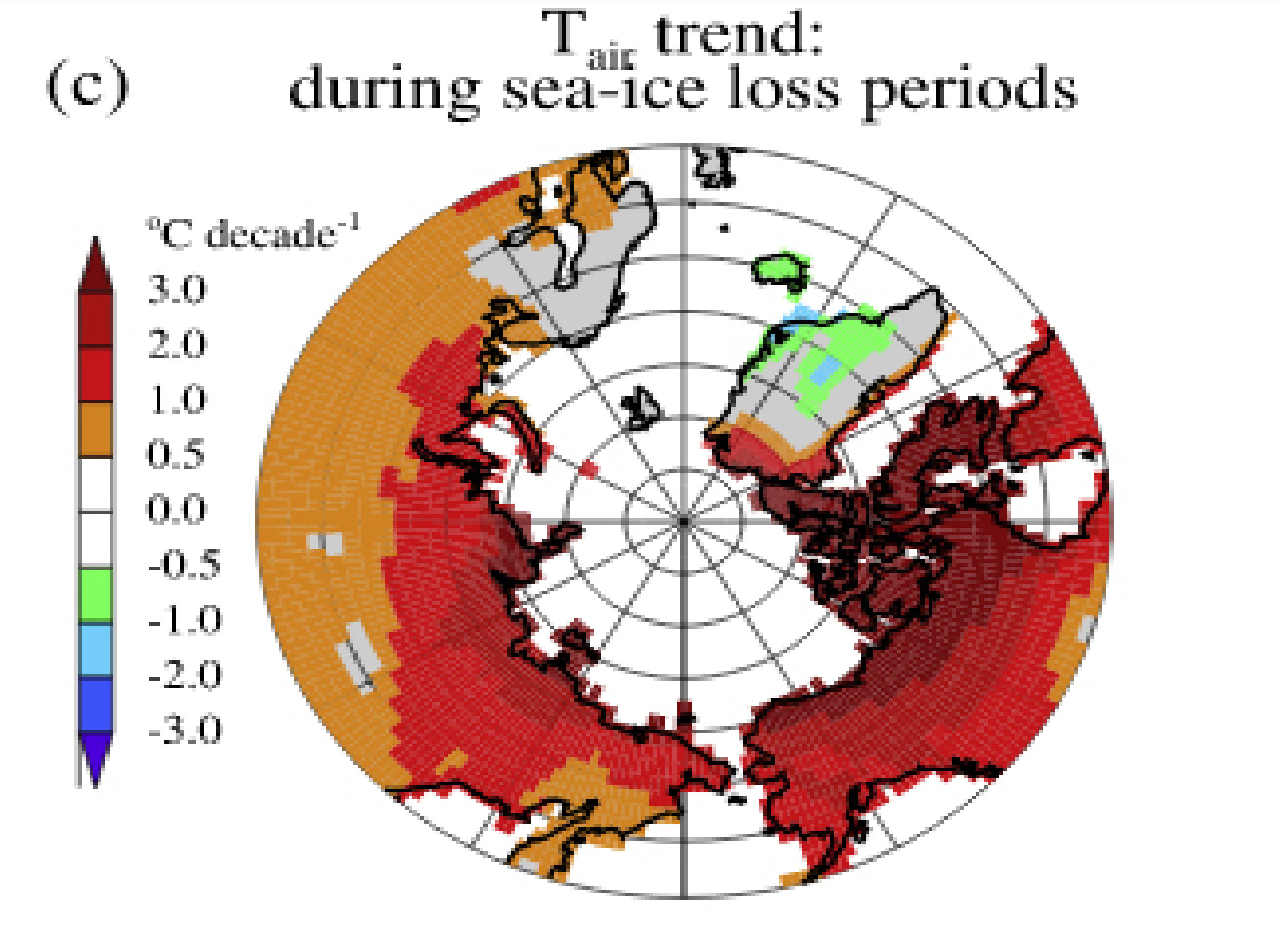


**New in 2019 – <u>twice</u> as much as we had assumed**. Northern peatlands alone: over 1 trillion tonnes,  2 times the total of all carbon humans have directly dumped into the atmosphere since pre-industrial days (**Nichols and Peteet 2019**, discussed **here**)

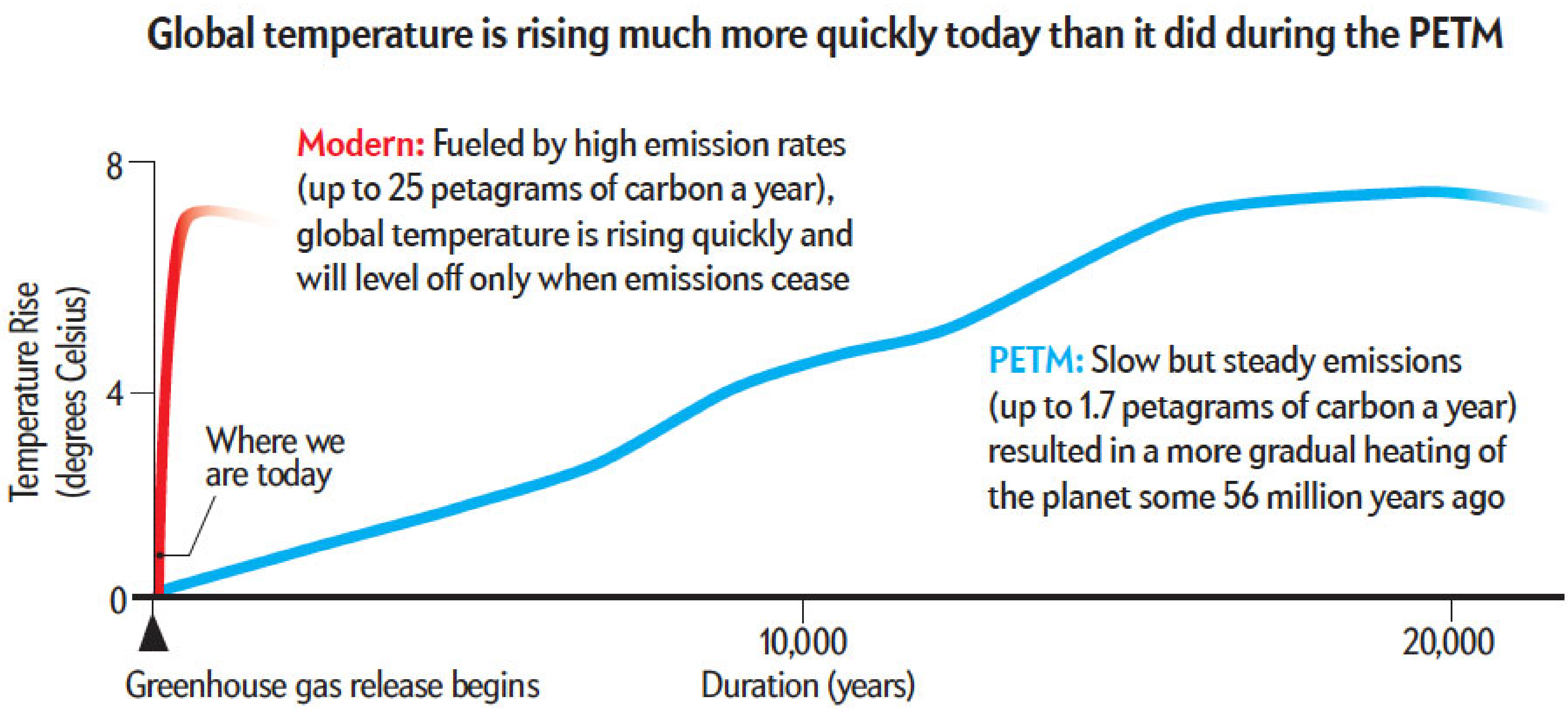
# The Arctic Ocean is only a few years away from losing all of its summer ice (Graph here is ice VOLUME).



**With sea ice loss, temperatures in the Permafrost rise from +1C to +3C <u>per decade</u>, and higher (Lawrence *et al.* 2008). This exceeds the "<u>Compost Bomb Instability</u>" limit. The Permafrost begins serious thaw above +1.5C (Vaks *et al.* 2013 and his later qualifications). <u>Climate forcing will exceed this</u>**



**Such Arctic rise rates are possible, especially given the Crowther *et al.* 2016 studies showing soil carbon loss as high as 17% that of human emissions. The rate at which we are forcing climate is unprecedented in Earth history – over 100x faster than even the PETM (Cui et al. 2011), for which this instability is a suspected cause.**



# Is this Just Doomist Nonsense?

- **A New research report** says a 3-5C temperature rise in the Arctic is "locked in" by 2050. (Fascinating look at the **UN's pushback on the conclusions of the scientists**. I can only read that to mean that the reality is perhaps worse still).
- Let's do a ballpark calculation using the Arctic at +2C above pre-industrial already (remember "Arctic Amplification" on top of global +1.5C)…
- 5C (2050) – 2C (today) in 30 years = 3C/30 yrs = **0.100 C/year temperature rise rate**
- That's  above the **0.088C/yr limit** triggering the **Compost Bomb Instability.**
- While complexities and uncertainties in soil conductivity etc. certainly exist, if triggered, it could produce very high and rapid rates of atmospheric GHG rise, and climate change much worse than we've looked at to this point.
- So far, the **Compost Bomb Instability** has not gotten much attention. Could it be part of the accelerating atmospheric methane concentration cause?

# A different planet Earth, less friendly to human life…

- What would a +12C temperature rises mean for the habitability of Earth? Sherwood and Huber (2010) in **the Publications of the National Academy of Sciences** find: (quoted from the abstract)…
- ***"Peak heat stress, quantified by the wet-bulb temperature (TW), is surprisingly similar across diverse climates today. TW never exceeds 31 °C. Any exceedance of 35 °C (95 F) for extended periods should induce hyperthermia in humans and other mammals, as dissipation of metabolic heat becomes impossible. While this never happens now, it would begin to occur with global-mean warming of about +7 °C, calling the habitability of some regions into question.***
- ***"With 11–12 °C warming, such regions would spread to encompass the majority of the human population as currently distributed today. Eventual warmings of 12 °C are possible from fossil fuel burning."***
- +7C is not that unlikely even on a path with significant efforts at reductions in direct human emissions.
- And land temperature rises will be significantly higher than the global average, since most of our planet is covered by high thermal capacitance water and ice

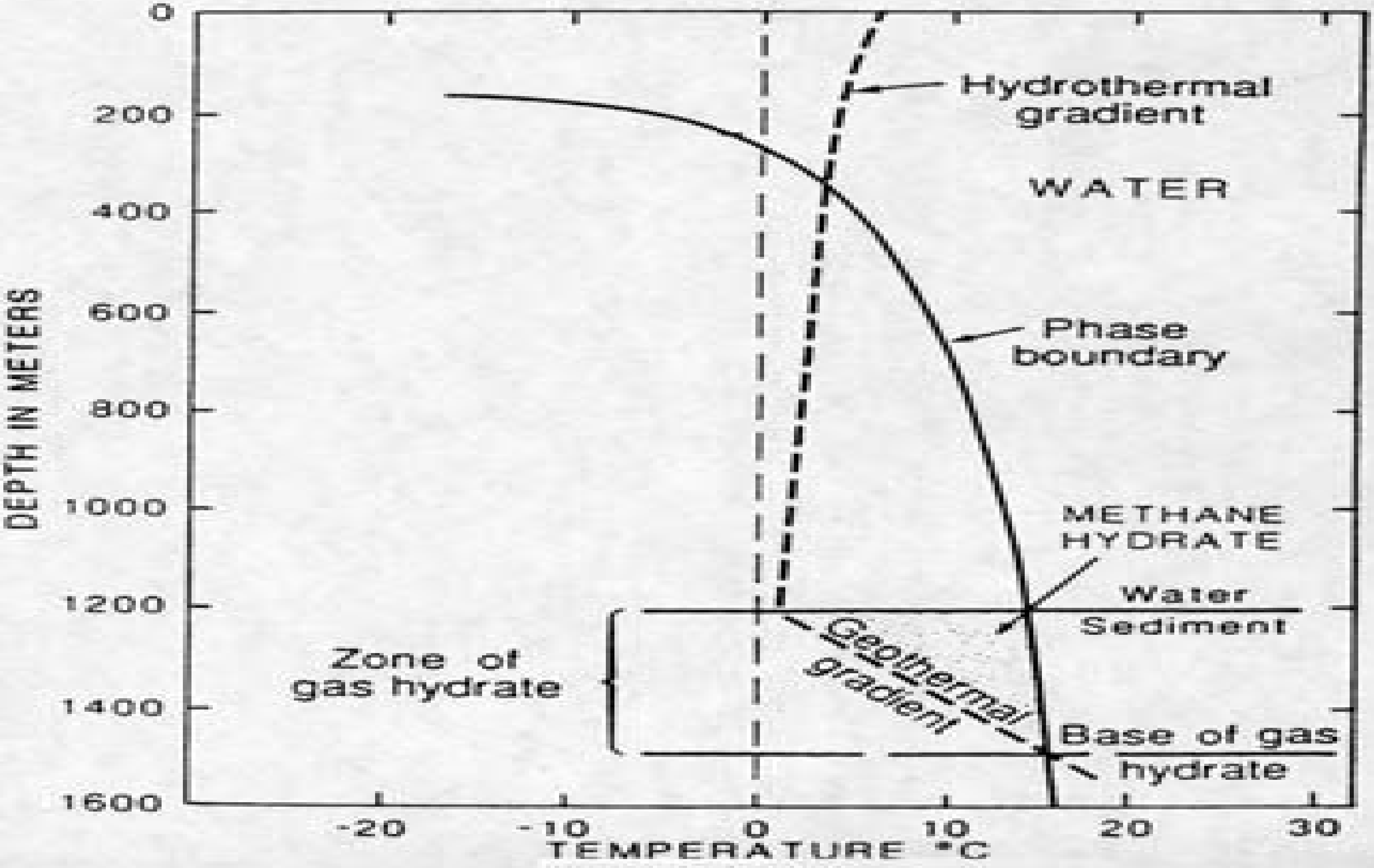
# 10b: Methane Hydrates

**There is more** that has not been included in the IPCC AR4 (2007) and AR5 (2013) assessment reports (which, after all, digest the published science of years earlier than these Assessment Report dates)…

# There are more methane deposits to consider besides those at the poles

- Methane hydrates along deep and shallow continental shelf ocean basins.
- Methane hydrates are held in stability by high pressure and low temperature.
- Higher temperature or lower pressure on these deposits can destabilize them, releasing methane as it transitions to a gas.
- Since this requires first absorbing the latent heat of clathrate formation, this process would not be explosive, but slow.

**As ocean temps rise, methane hydrate turns to a gas, rising into the atmosphere. While rising sea level would add pressure, which helps stabilize methane hydrate, at shallow levels reachable by the heat, it Will Not Be Sufficient to Counterbalance Higher Temps, It is Calculated.**



# Methane Release from Sea Floor Methane Hydrates?

Methane hydrate is less dense than water; it therefore floats. Sudden sharp release of only 10% of this store would cause climate forcing <u>10 times</u> that which $CO_2$ is doing today.

- Is this possible? How stable? see **Archer, D. (2007)**
- **<u>Most researchers consider it unlikely that Arctic methane clathrate release can be abrupt</u>, since the pressure necessary for clathrates is only found at 350 m depth and greater, and this is far below the sea bottom of the Arctic Ocean continental shelves where they may have formed in past Ice Ages, and where future warming is greatest. Heat conduction to these hydrates will take many centuries, hence no sudden sharp release.**
- **We see no evidence of abrupt Arctic methane release today, only low level leakage from the continuing thaw of shallow continental shelf which had frozen carbon during last Ice Age**

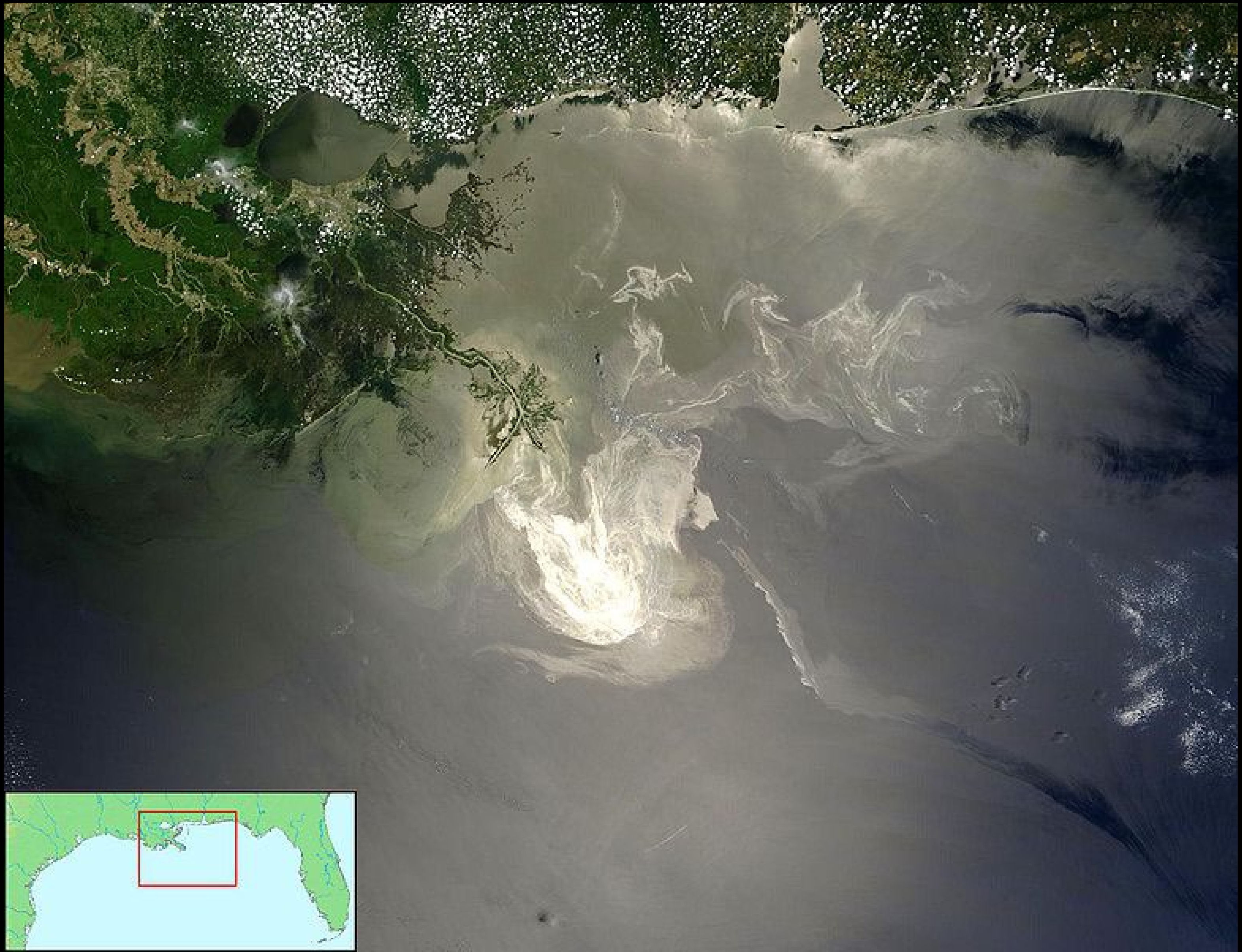
# How are the Oil Companies Thinking about Methane Hydrates?

- I leave this as a brief "gedanken experiment" (a "thought experiment", in the spirit of Einstein) for the student…

# OK. Here's the Answer…

- Fossil fuel corporations are investing hundreds of millions of dollars into exploratory work for **mining methane hydrates as a commercial fuel source**.
- To say the least, this is incredible….
- **We have already seen drilling destabilize deep sea methane hydrates - causing the Deepwater Horizon Explosion and resulting Oil Disaster in the Gulf of Mexico in 2010**

# 2010 "Deepwater Horizon" oil disaster, from satellite imagery



# So, That was Bad. But Since then, the Oil Companies Have Surely Learned How to Drill Safely….

- …..right?

# No. Shell Oil's Alaskan Drilling Rig, Wrecked by Storm Waves Dec 31, 2012

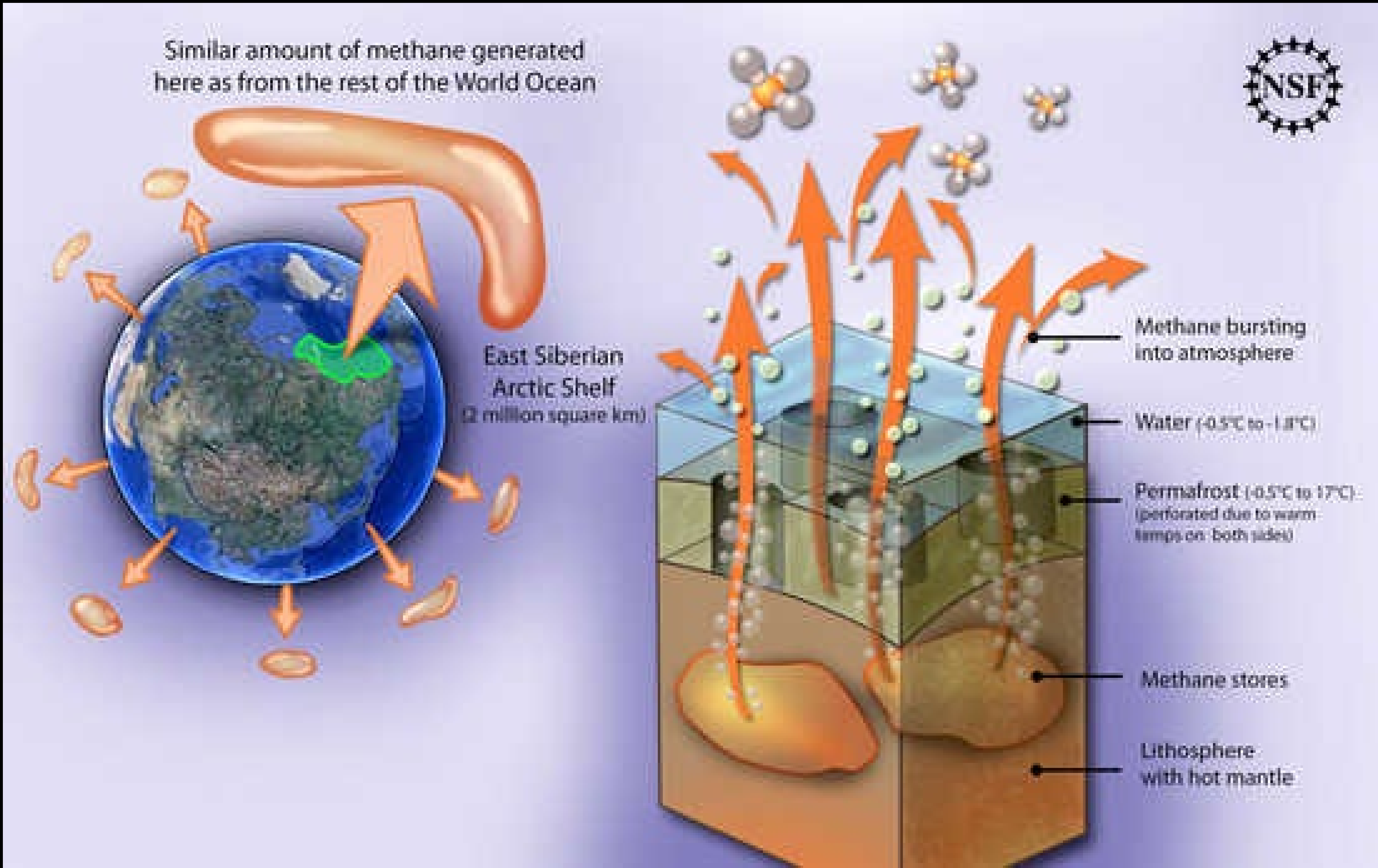
# Maybe Shell Oil and the Others Should have Considered…

- …That since they've helped the Arctic lose most of its sea ice, and it is projected to soon lose all of its summer sea ice – that Arctic Ocean waves which had been tiny due to the small open water wind fetch, are rapidly getting more powerful, given all the new open water.
- …Arctic storms will strengthen, and so the summer season (the only season when oil drilling can happen), will be much more dangerous for drilling than it is now.
- Even more dangerous are more large icebergs, which meander uncontrollably, destroying anything they run into.
- Think of an oil rig as a mosquito with its mouth parts stuck into the sea bottom, as the iceberg (like your hand?) bears down
- In 2015, Shell Oil was given permission to resume drilling in the Arctic, by the Obama Administration.
- **This is sheer madness! Yet, their response instead is…**

# “We’re Gonna Need a Bigger Rig”

- **The Arctic Ocean is Estimated to hold 13% of Global Petroleum. So, even though Shell Oil acknowledges the reality of CO2-caused climate change, the money was just too big to pass up (source).**
  - **Now as of 2016: Shell has decided to give up this quest**

# Methane release from frozen but thawing subsea deposits, (from NSF)



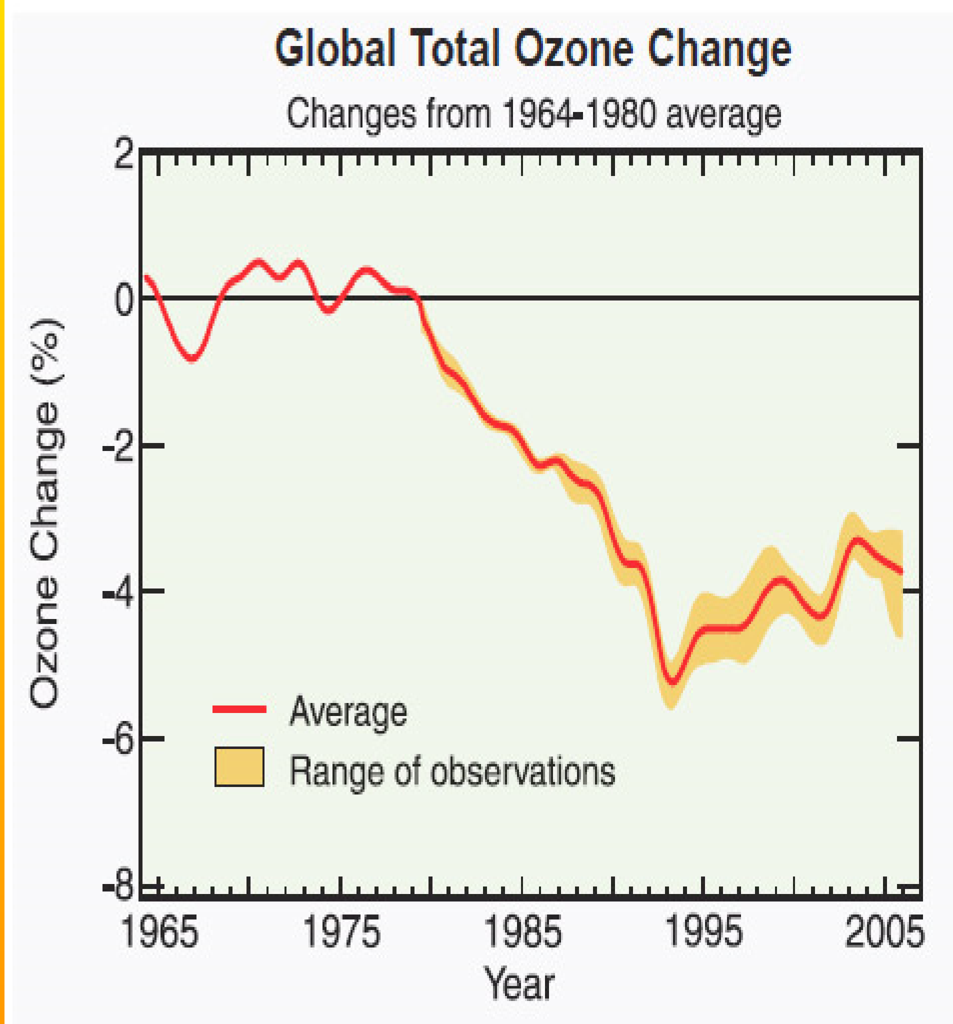
# Methane Hydrate Release to the Atmosphere - Effect on Climate?

- Methane release from the Arctic is simply not well enough studied yet. We don't have enough monitoring stations, and release rates so far as we have seen, can vary on short time scales by large amounts.
- Climatologist Dr. David Archer has argued that most or all of Arctic methane clathrates must be (to have formed in a stable way in the first place) deep enough under ocean sediments that heat flow to cause their melting must be very slow, so abrupt climate change from Arctic Ocean clathrates is not a significant danger.
- But ongoing slower methane release could very well be unstoppable given our climate forcing. Slow release will oxidize to CO2, so "abrupt climate change" is far less likely

# 10c: Ozone Changes

- Thanks to chlorofluorocarbons (CFC's) used as refrigerants for many decades, the stratospheric ozone layer has thinned.
- This lets in more UV from the sun, raising skin cancer rates and harming crops.
- The Montreal Accords banned CFC's from the developed world, but gave a longer term reprieve for the developing world.

# Stratospheric Ozone's Very Slow Recovery

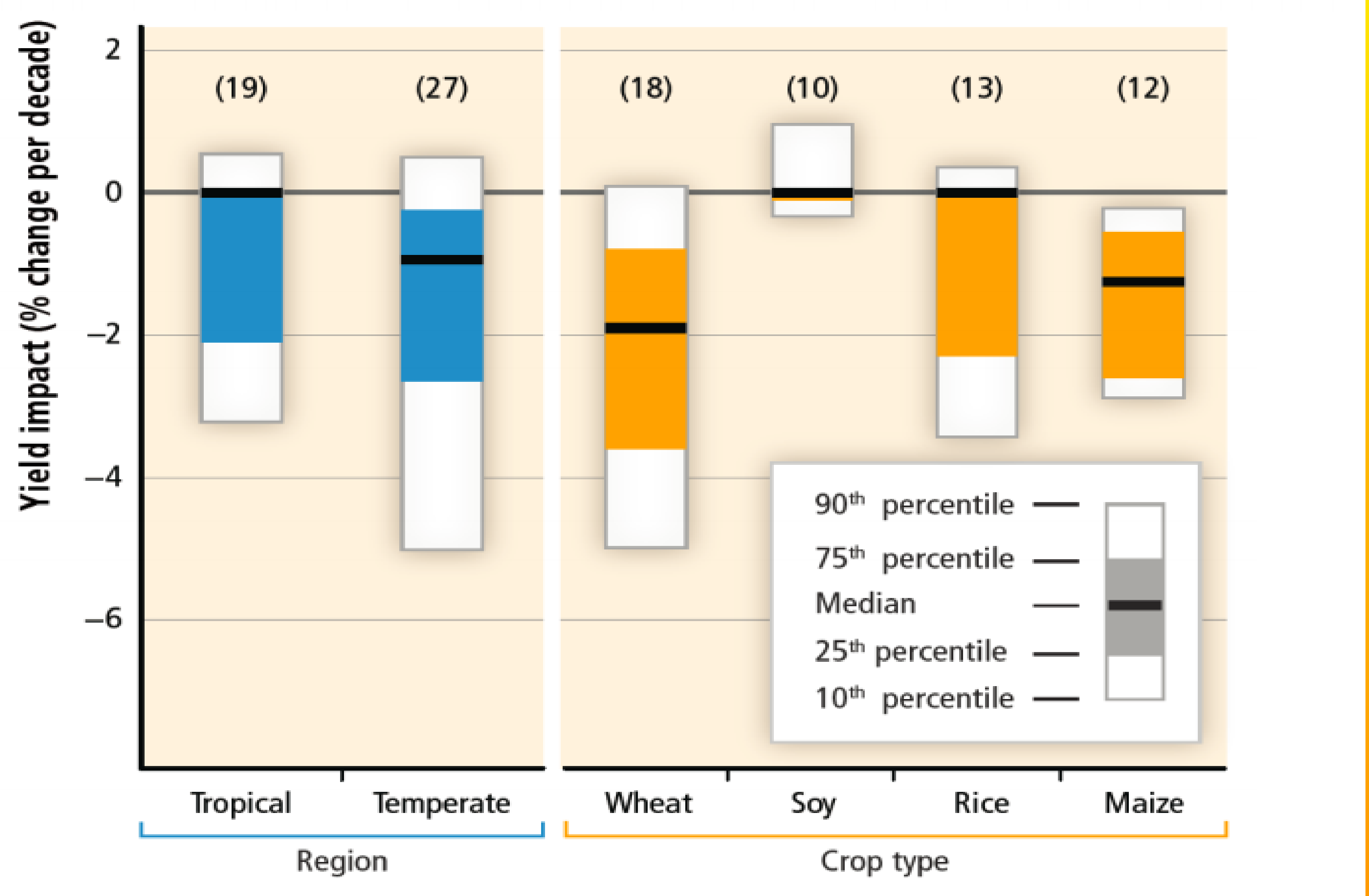



- This latter, together with the CFC's "banked" before the stopping of manufacture, means that stratospheric Ozone levels have only barely started to rise in past decades.

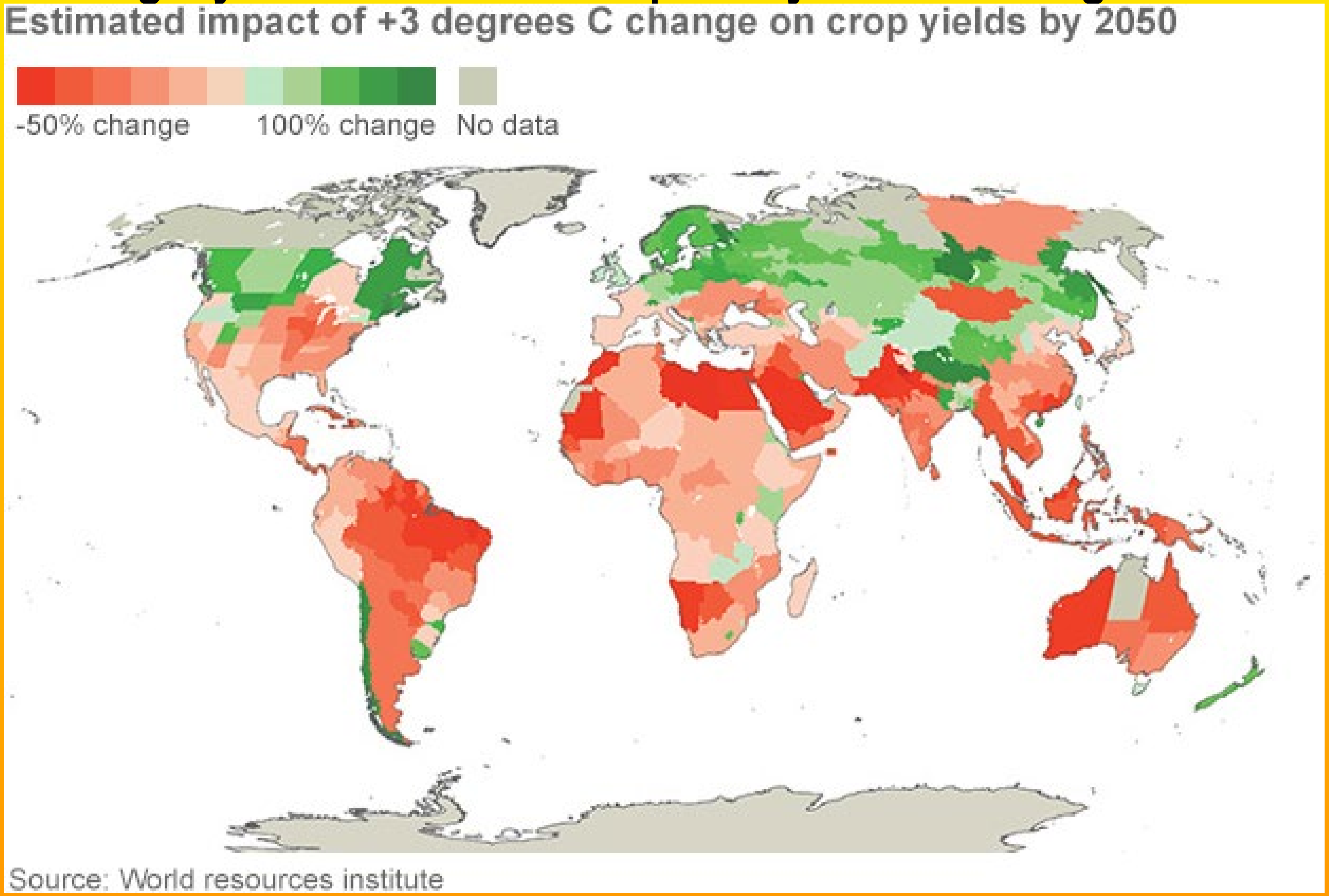
# We want stratospheric ozone to recover. But be careful what you wish for…

- This will **add** to global warming.
- Why? Because ozone is a greenhouse gas, impeding outgoing IR from the lower atmosphere and ground radiating to space.
- Now, it also absorbs incoming solar energy that would otherwise reach the ground, acting to cool climate a bit, but the GHG effect dominates, and so the loss of our ozone has actually been a net COOLANT to our climate, by a **very strong 0.5C per decade since the 1970's**
- **By repairing stratospheric ozone, we amplify global warming.**

# 11. Staple Crop Yields Drop with Climate Change



**Even just +3C temps mean most of Earth has poorer (red) crop yields, up to <u>50% loss</u>. The worst effects are in the most populated areas. Note the devastating effects on the Arab Countries. Then ponder their rapid population rise, their violent political instability, and imagine the Syrian tragedy of this decade multiplied by orders of magnitude.**



# Climate Denialists Like to Promote the Meme "More CO2 is GOOD for Plants!"

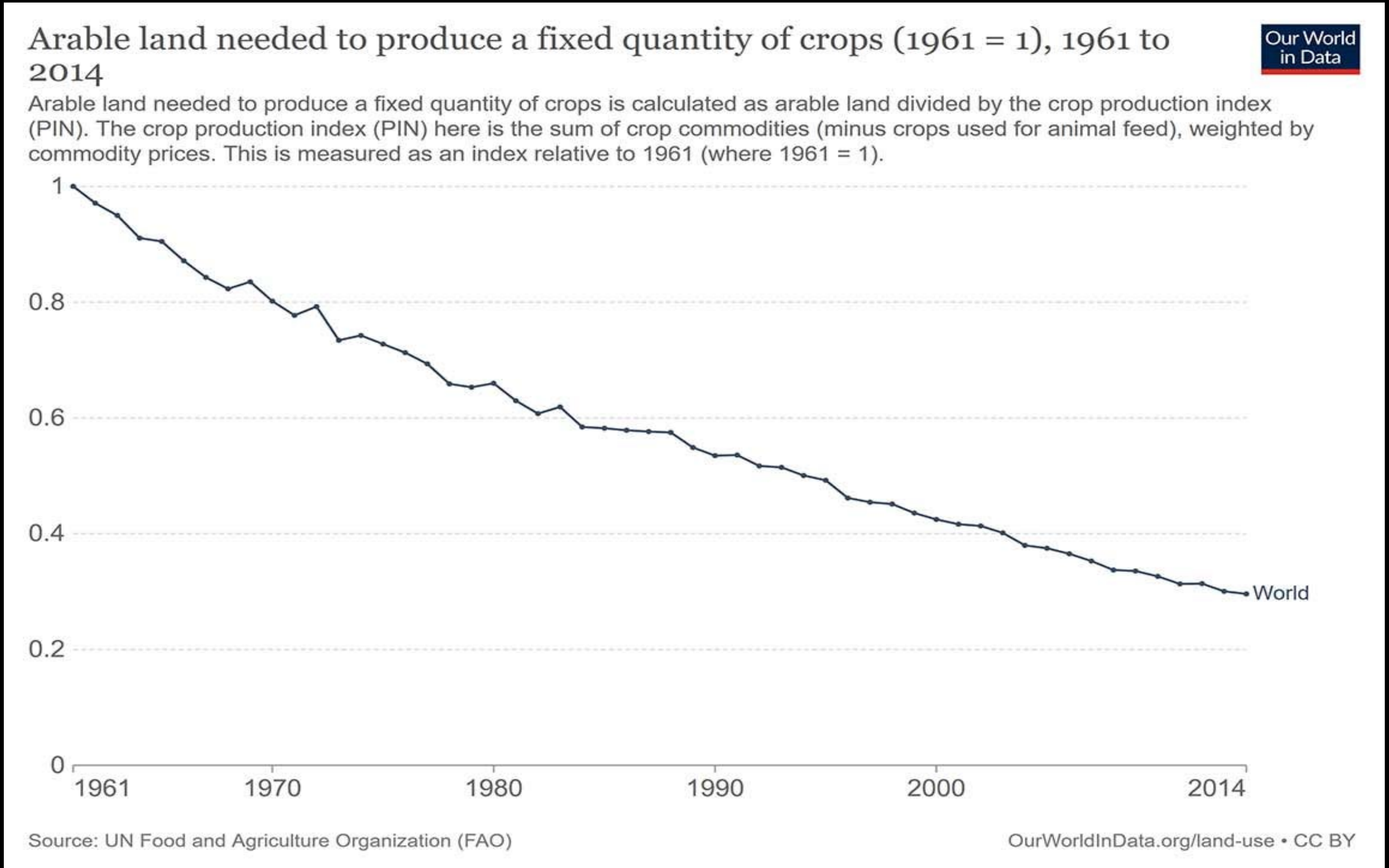
- But, it's just another lie.
- Yes, higher CO2 (up to a point) makes plants grow faster (assuming they still have good soil and water), but a more accurate description for crops is that they "bolt" and go to seed faster
- **And the actual valuable edible parts of plants are smaller and poorer**, requiring MORE plants to make up for the deficit.

# Worse, competing weeds grow up to 3x faster than food crops in global warming conditions

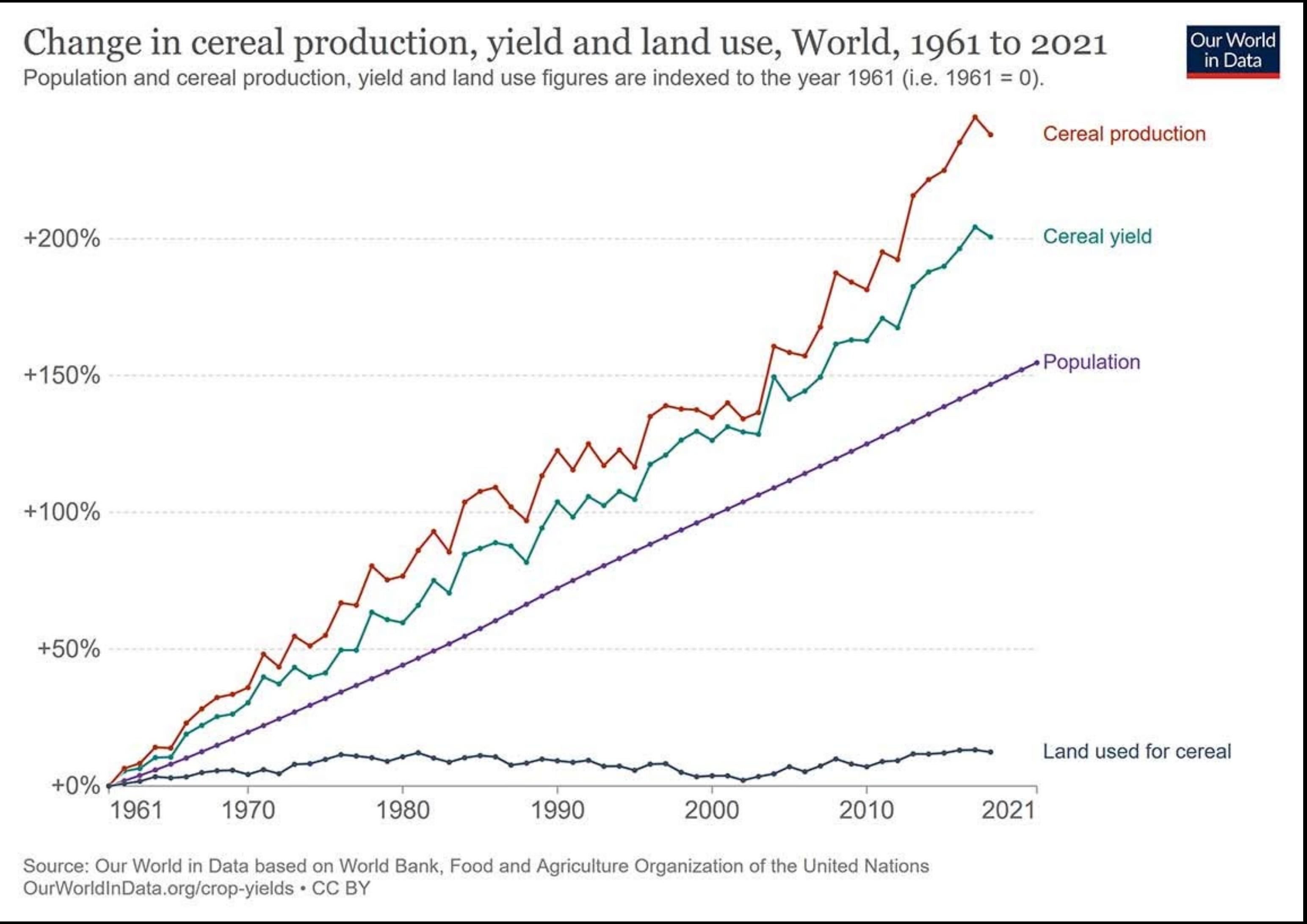
# Pressure for increased use of Monsanto's *Round Up* and its carcinogenic glyphosate (already at high levels in American food)

- Worrisome – but the Trump Era's FDA has implemented a "solution" (to the worry): we'll just stop testing crops for the herbicide.

# So Far… More use of artificial fertilizers, high-energy consumption high tech farm machinery has been yielding more crops per acre



# So Far… yields of staple crops have thus kept ahead of rising population



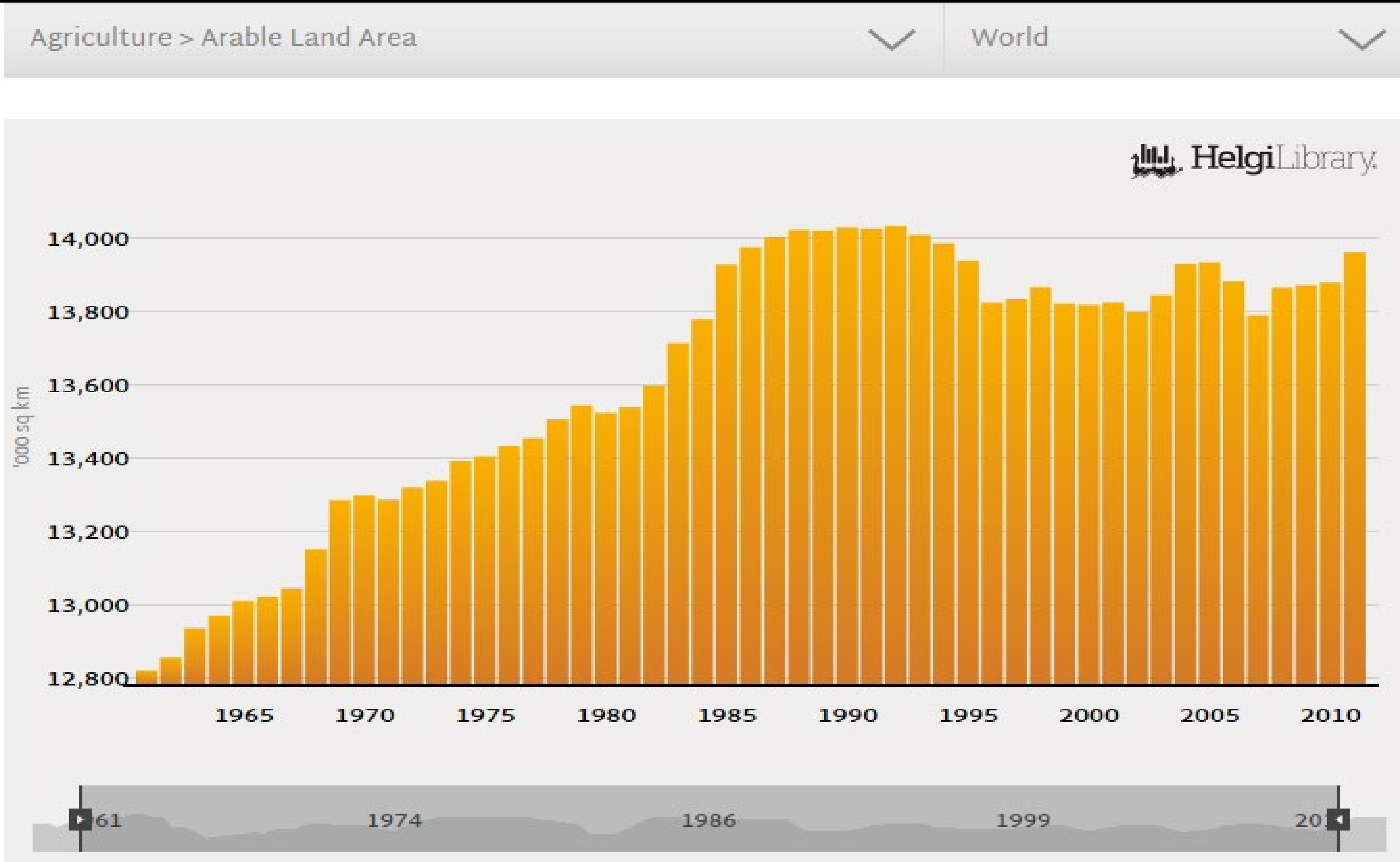
# But as Temperatures rise… can we GMO tougher crops?

- We've had some success engineering more drought-tolerant plants.
- **But biology is extremely temperature dependent, and despite 30 years of major efforts, there has been NO success at breeding heat-tolerant staple crops (1:04:50 into this talk by atmospheric scientist Dr. David Battisti in 2016**).
- And elevated $CO_2$, far from being "good for plants", is robbing food crops of vital nutrients (**Myers *et al.* 2014)**

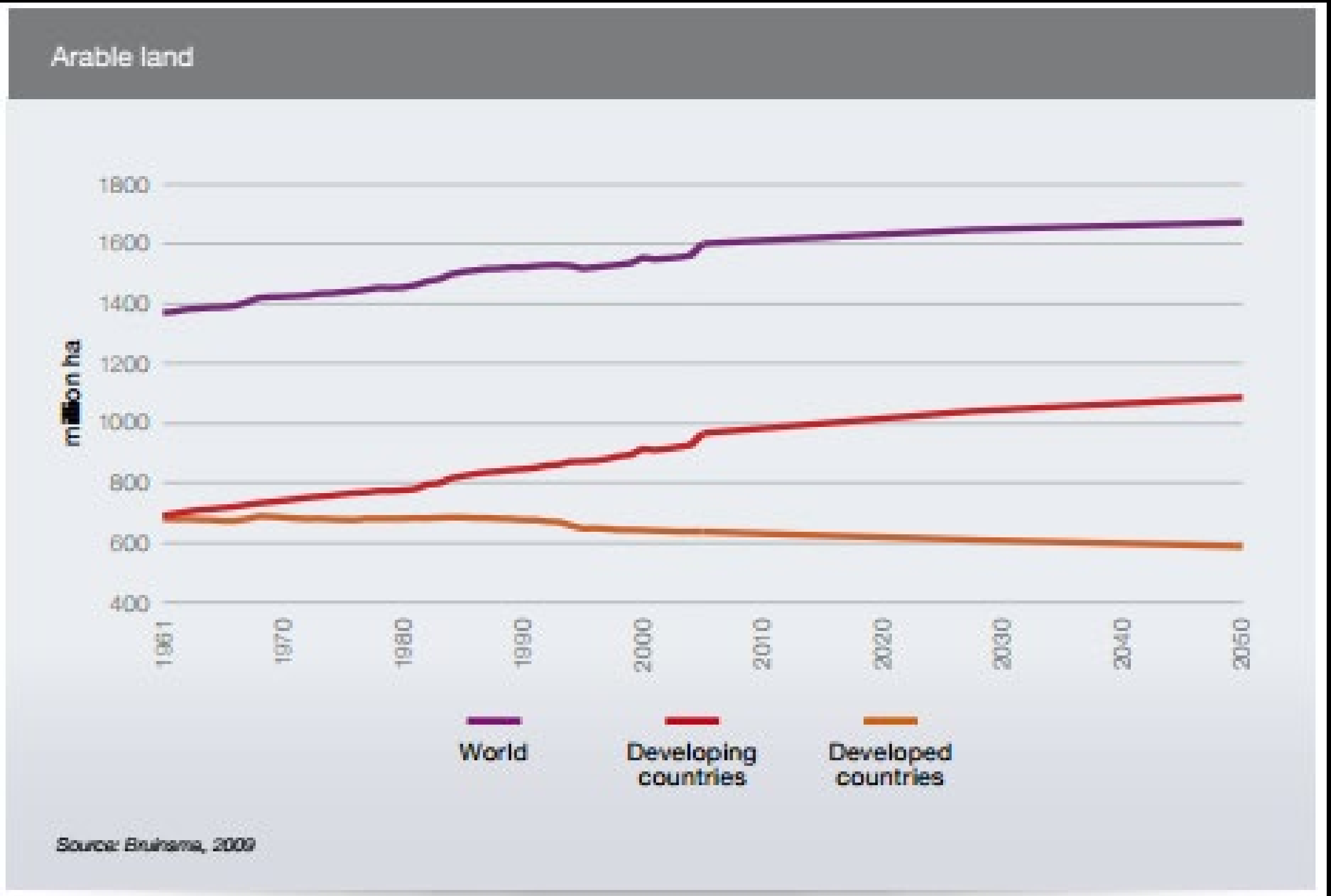
# These Only Consider the Effect of Drought and Temperature on Crops – What about Soil?

- **Existing arable land topsoil is being washed away at a rate of almost 1% per year, because large-scale disc'ing of land which needs little labor. This robs soil of roots and other organic holds. It also releases $N_2O$ (a greenhouse gas) from mass use of nitrogen fertilizers (which also minimize costs *vs.* labor-intensive organic methods). Cost rules the decisions, as always.**
- Topsoil creation from rocky subsoil: rate is only ~1 cm per 1,000 yrs by natural forces, (assumes healthy plant cover).
- With current commercial agriculture techniques which strip soil of nutrients and prevent "weeds" from holding soil in rain storms, this suggests to some, that **farming might survive for only another 60 years.**

# Total area of arable land has plateaued. While depth of topsoil continues to erode



This source below is more optimistic: bringing on-line more crop land (but, to be similarly washed away??). Additional convertible land is very scarce, especially in developed nations, who are losing arable land the fastest (bottom curve)



# By 2050, the amount of arable land per person will <u>drop to only ¼ of what it was in 1950</u>

- Large fish in the ocean are down ~90%
- Phytoplankton abundance is dropping
- Most shellfish as well, both from warmer surface waters and growing acidity, especially off the West Coast of the U.S, where <u>reproductive failure of shellfish has been underway now due to growing acidity.</u>
- So what will we eat then?  (a student suggested Soylent Green).

# Highlights from Battisti's Talk: "*Climate Change and Global Food Security*"

- We need to double our staple crop yields in the next 35 yrs
- Requires increasing yields at a rate we have only accomplished once, near the end of the "green revolution" some years ago, and we have to do it continually for a much longer period of time. And yet…
- ~all agro suitable land is already in use, and we're losing it at 1%/yr due to erosion, salt intrusion, wind…

- Water? Already in short supply and dropping, opposite to what we needed during the “Green Revolution” (which was made possible by adding ~100x more energy to agriculture than prior – energy which helped add CO2 to our atmosphere).
- Only 50-300 yrs of global supply of phosphorus (P) is all that remains. P and N (nitrogen) are both essential to plants.
- 50% of the food for the tropical populations is the staples: rice, wheat, maize - which are in trouble because in the tropics they are already above their optimal temperature range.
- **Therefore, expect steeply falling yields as temperatures continue to climb**

# What about Vegetables?

- Not good...
- A new study in PNAS (**[Sheelbeek *et al*. 2018]**) discussed **[here]**, finds that vegetable yields will **drop by ~33% by 2050** on our current path.

# 12. $CO_2$ Effects on Global Insect Populations and the Food Chain

## America's own Luquillo Rainforest in Puerto Rico is ground zero of the global insect apocalypse

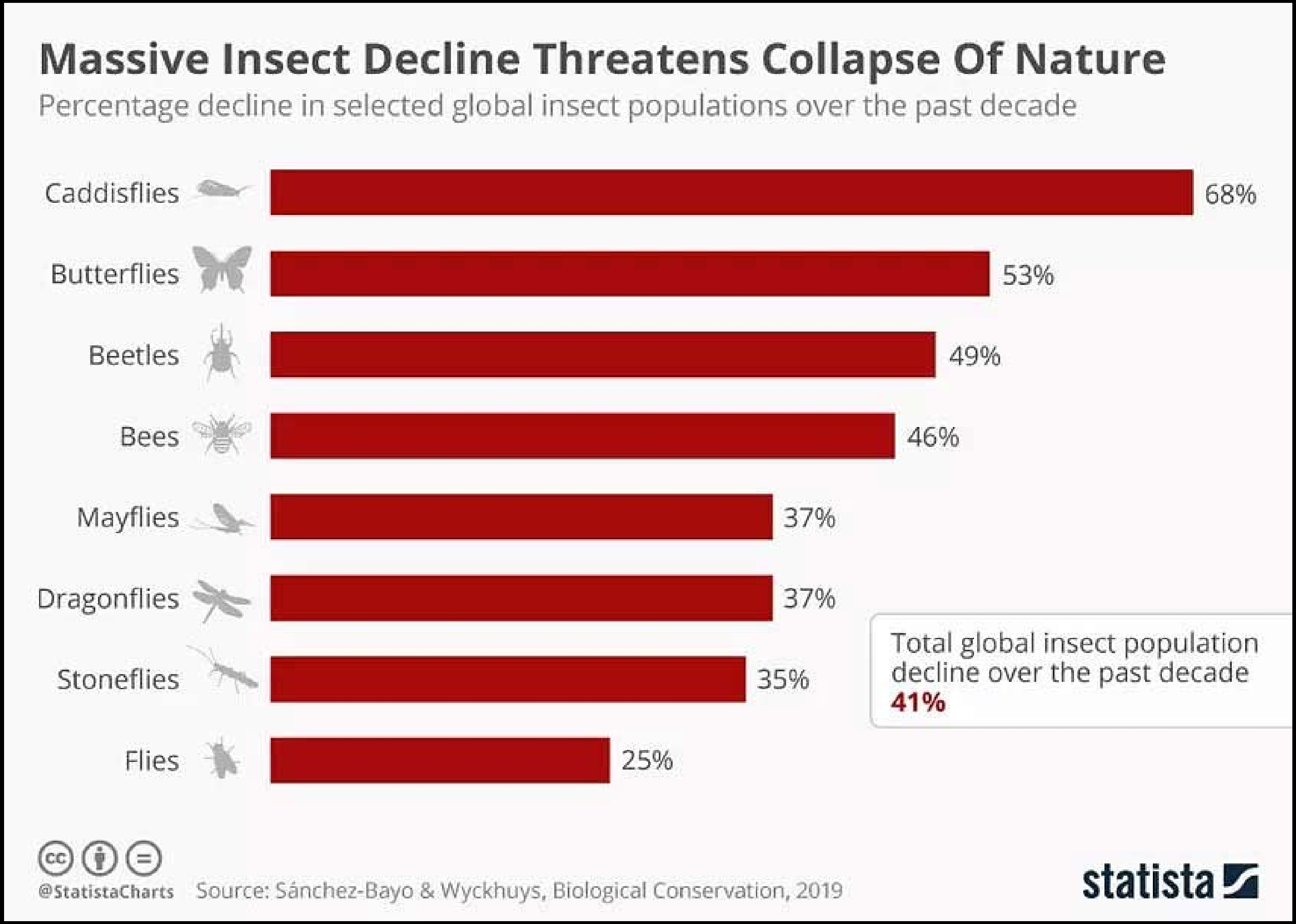
Far from human agriculture and pesticides the insect apocalypse is at its worst

Newly published scientific report documents cataclysmic disappearance of tiny life by 10-60 times! As little as 1.6% of tiny life remains.

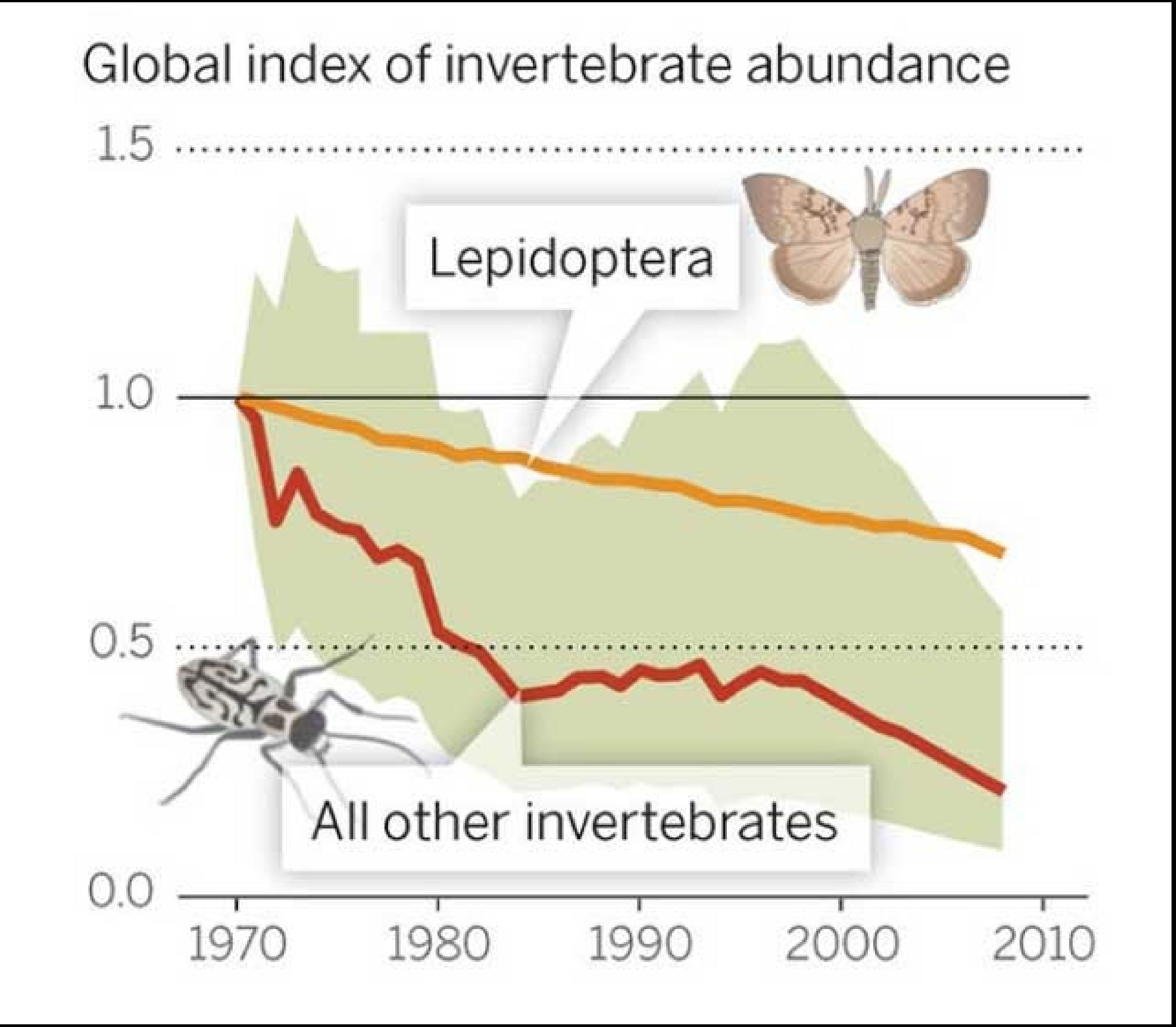
# Causes are multiple and need clarification, but appear to be heat stress, habitat loss, pesticides

- A new Review article of general insect population global losses (Sanchez-Bayo and Wyckhuys 2019) find **losses of approximately 58% in just the past 18 years**
- Globally, insect populations are declining at a rapid 2 - 4.3% per year, depending on **source**

# From Sanchez-Bayo and Wyckhuys 2019. That's a 41% decline in 1 decade



# Insect Loss: From 1971 to 2008 ~75% Reduction in Abundance



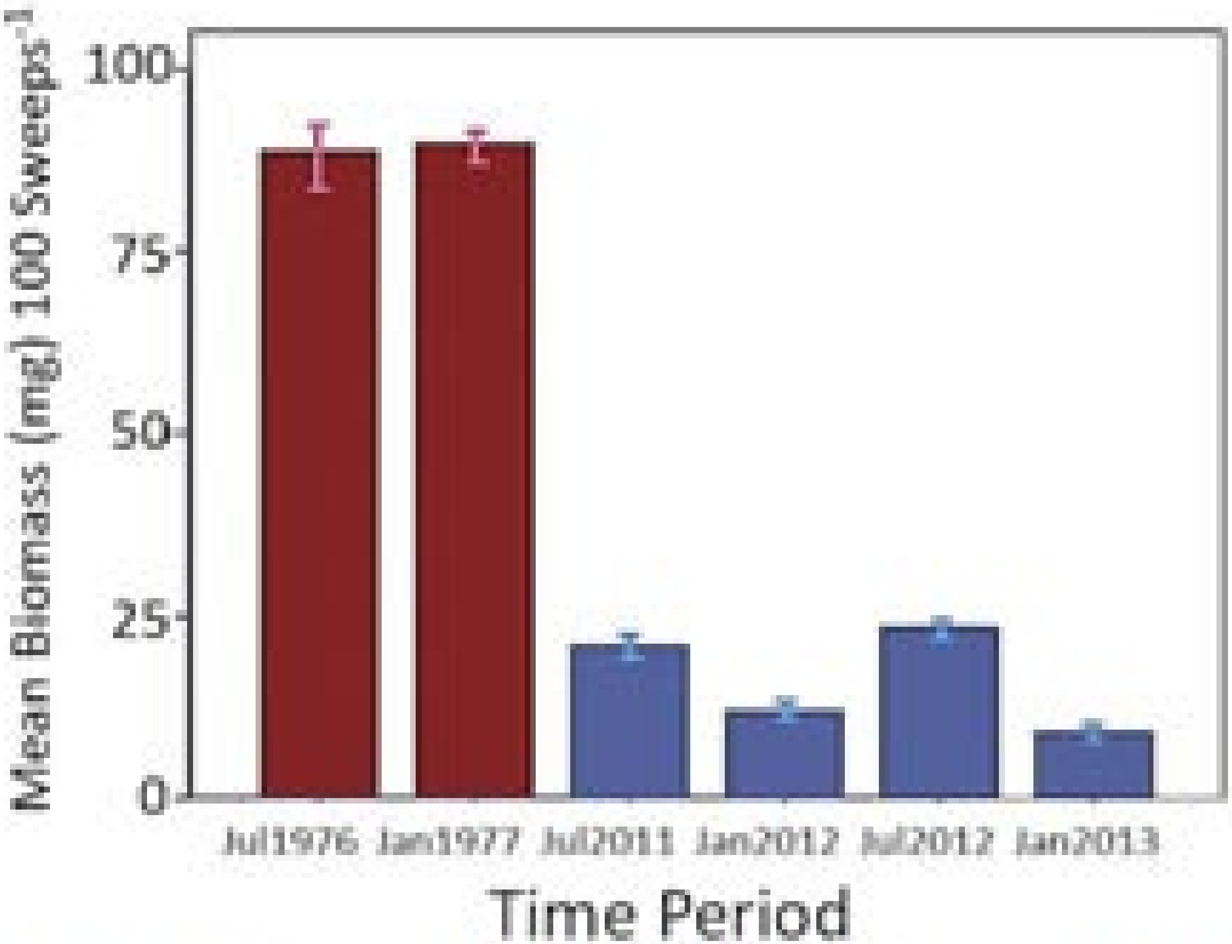



Fig. 2. Mean dry-weight arthropod biomass per 100 sweeps taken in the same sample area in the Luquillo rainforest during July 1976, January 1977, July 2011, and January 2013. One SE around the mean biomass is shown for each bar. Total sweeps taken in each period was 800, except for July 1976, when 700 sweeps were taken. Data for 1976 and 1977 are from Lister (22).

Lister and Garcia

**In the 37 years since their first census, biomass of insects in the Costa Rican rainforest has dropped by a shocking ~85%**

# 13. Regional Climate in the Future: Drought over the populous zones, increased rain over the equatorial oceans, and poles (UN report). This figure is from the IPCC AR4 and therefore very likely too optimistic, as we've seen

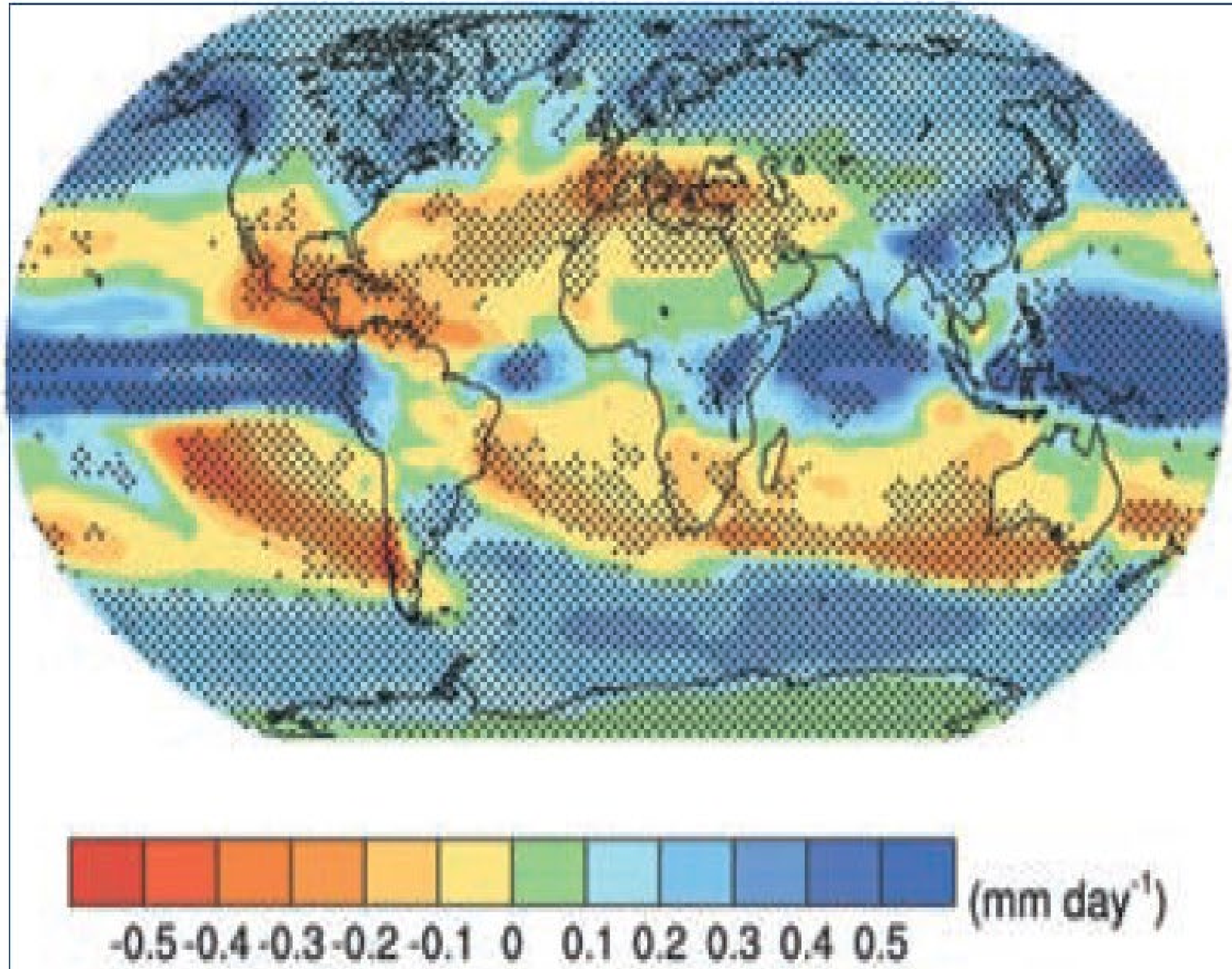



**Figure 11:** By 2099, precipitation is expected to increase in the Arctic and decrease in temperate zones based on this multi-model mean from the IPCC Fourth Assessment Report. The units are millimeters per day and the changes are annual means for the A1B scenario for the period 2080 to 2099 relative to 1980 to 1999. Stippled areas indicate where at least eight out of ten models agree *(IPCC 2007, Figure 10.12)*.

# On Previous Slide – the Good and the Bad News…

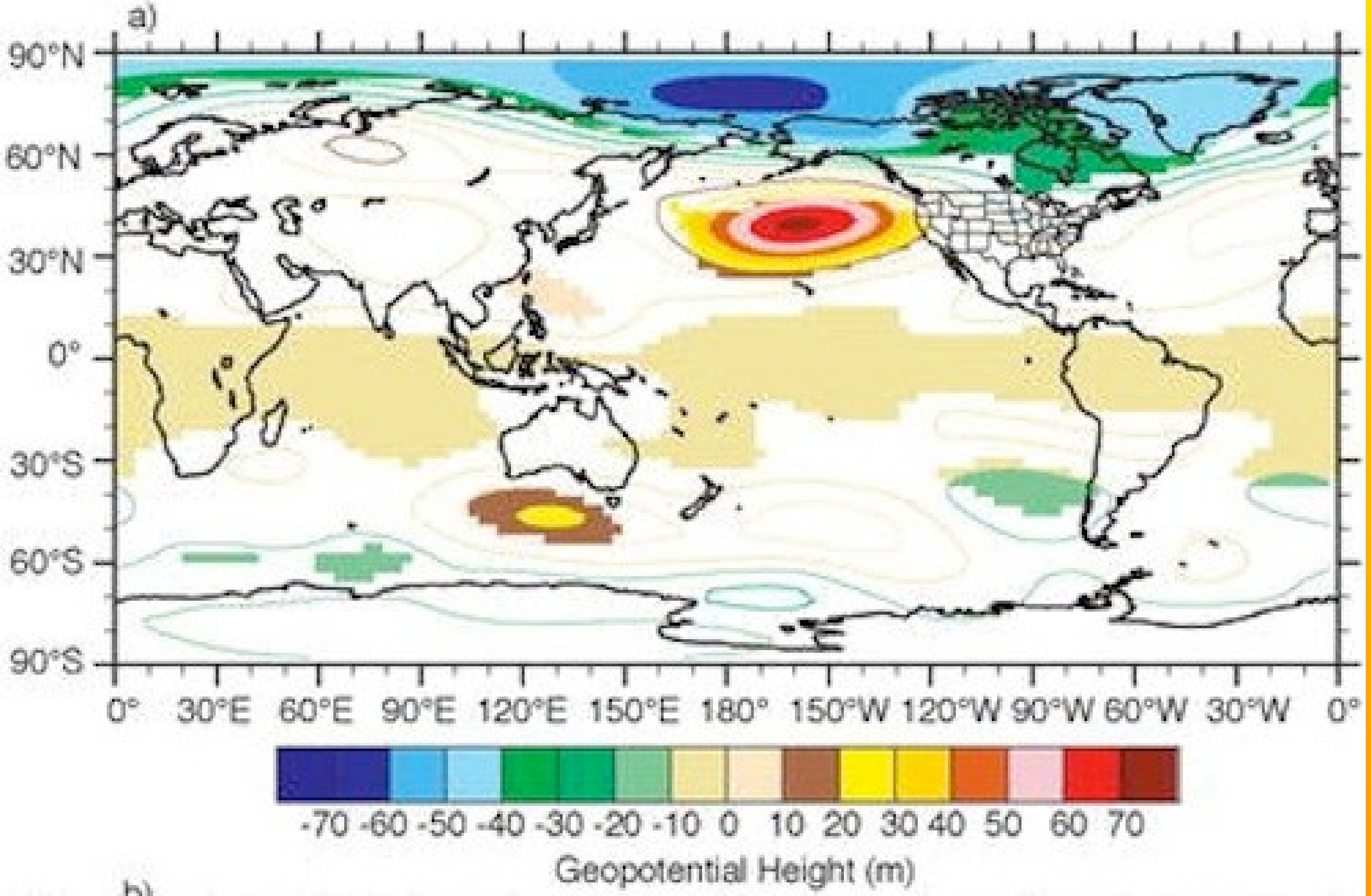
- The good news is, there's going to be more rain from the more humid climate
- The bad news is – it's going to fall mostly over the Arctic (where it contributes to wetlands producing more methane from thawing permafrost), and over the tropical oceans, which does no one any good.
- Over mid-latitude continents – where **people** live - we'll instead have **increasing drought.**

# Regional Forecasts: California

# California Forecast: Drought

- **Oster *et al.* 2009** studied stalagmites from Moaning Cavern, CA; age dated via Uranium/Thorium ratio, and temperature, rainfall data from other element ratios, and correlated with Arctic from existing paleoclimate records…
- They find… that **when the Arctic Ocean thaws, we get drought in California**, as the polar jet stream migrates north, according to climate models (yes, it "wiggles" more, but the average position of the polar jet stream is farther north)
- That is exactly what we are already seeing now.

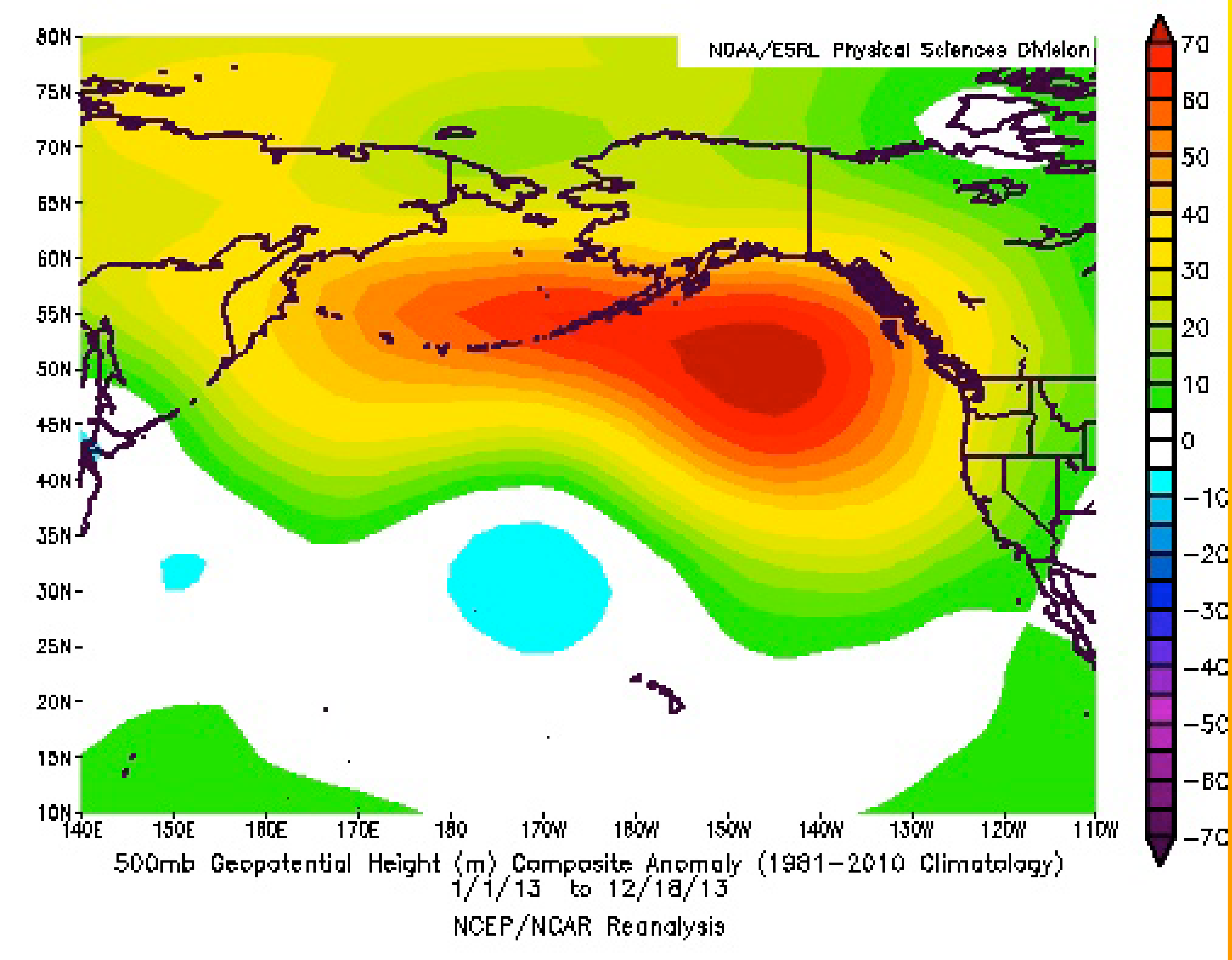
**Sewall and Sloan's (2005) Climate Modelling Studies Predicted the Emergence of "The Blob" … a Mass of Hot Water Deflecting the Jet Stream Northward, due to Melting of the Polar Cap**



# It is the loss of Arctic Ocean ice which causes this pattern.

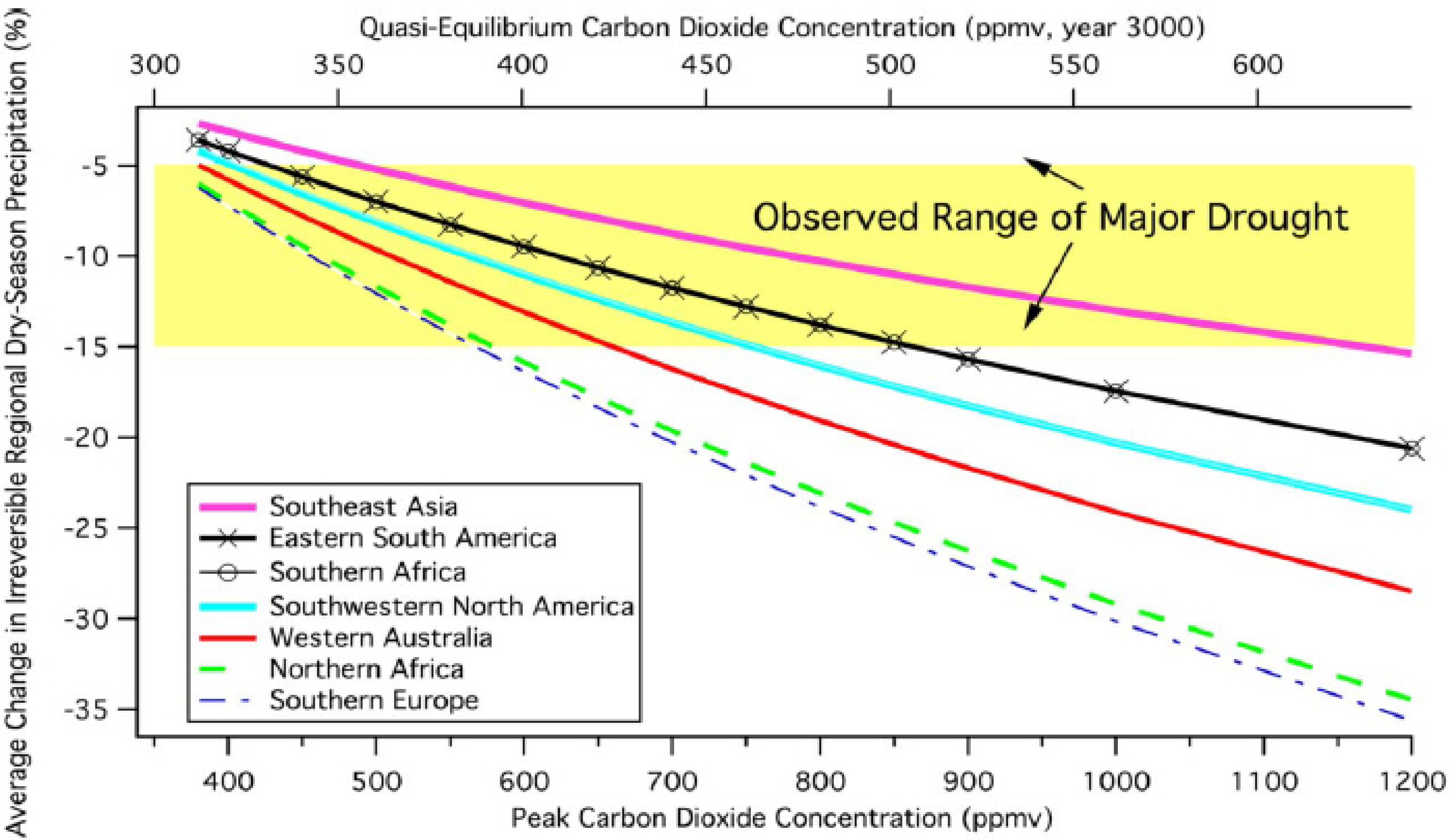
- Co-Author Jacob Sewall*: "Where the sea ice is reduced, heat transfer from the ocean warms the atmosphere, resulting in a rising column of relatively warm air. The shift in storm tracks over North America was linked to the formation of these columns of warmer air over areas of reduced sea ice."*
- ***"Both the pattern (of real 2013 data) and even the magnitude of the anomaly looks very similar to what the models predicted in the 2005 study."***

**<u>And indeed, "The Blob" - is here</u>. Below is real observations: Mapped is the average for all of 2013. It is predicted to be <u>Persistent, and Worsen</u>. Although some years it may migrate elsewhere (such as 2019).**

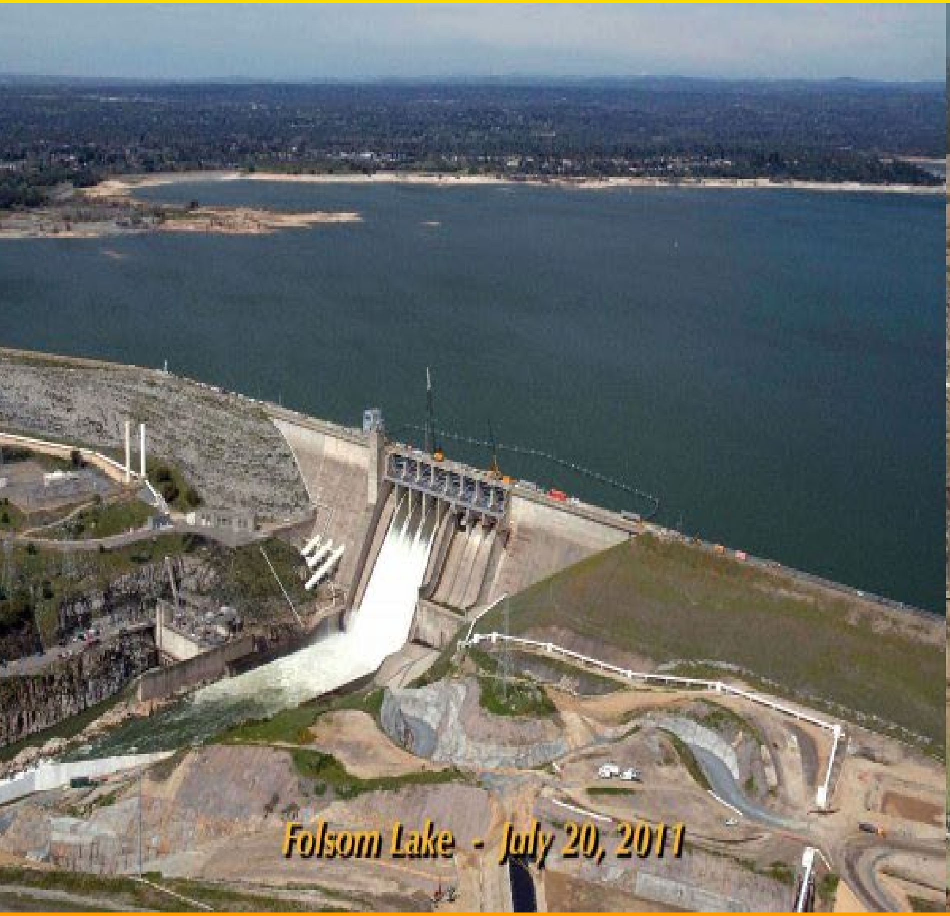


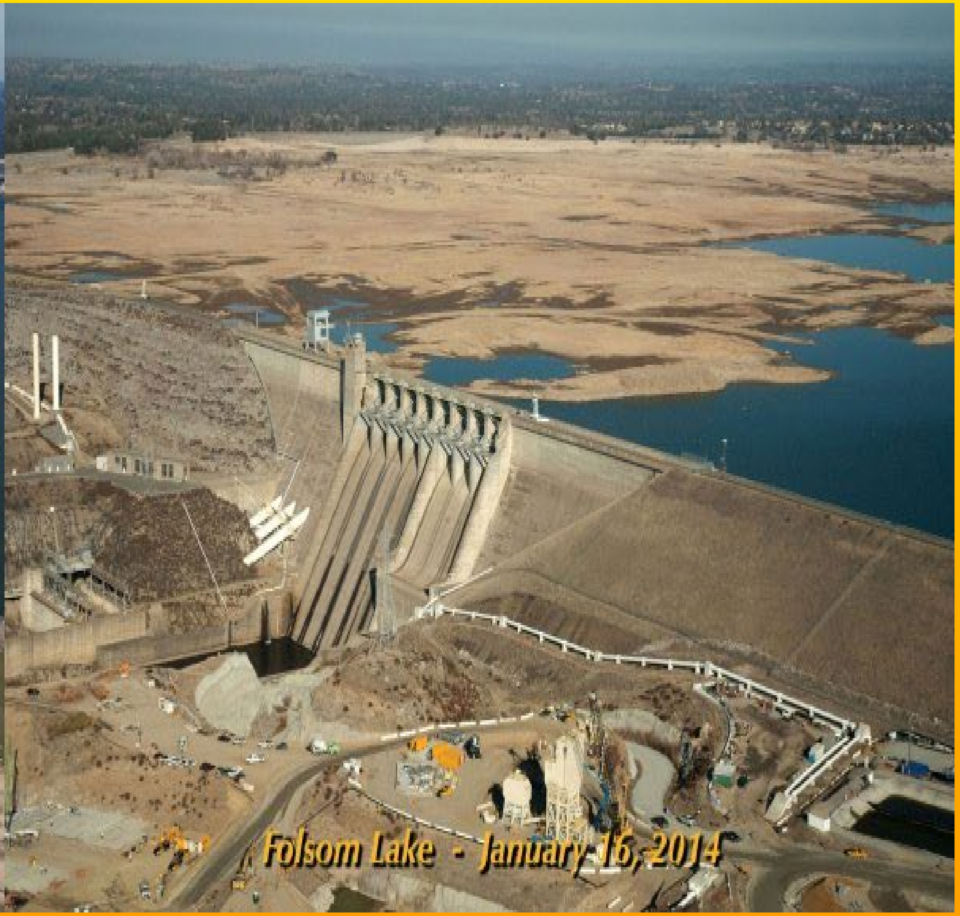
- **Sloan:** *"Yes, in this case I hate that we (Sewall & Sloan) might be correct. And in fact, I think the actual situation in the next few decades could be even more dire that our study suggested. Why do I say that?*
- *(1) we did not include changes in greenhouse gases other than CO2;*
- *(2) maybe we should have melted more sea ice and see what happens;*
- *(3) these atmospheric and precipitation estimates do not include changes in land use, in the US and elsewhere. Changing crops, or urban sprawl increases, or melting Greenland and Northern Hemisphere glaciers will surely have an impact on precipitation patterns."*

# Worsening Droughts – U.S. Southwest (blue curve). Likely far too conservative, as these are the same models which badly underestimated Arctic Ice Loss



# With Less Rain and Snow, Reservoirs Dry up



**Oroville Reservoir in 2014. California Headline in Spring ’15 – *“One year of Surface Water Remaining.” (El Nino provided a brief reprieve)***

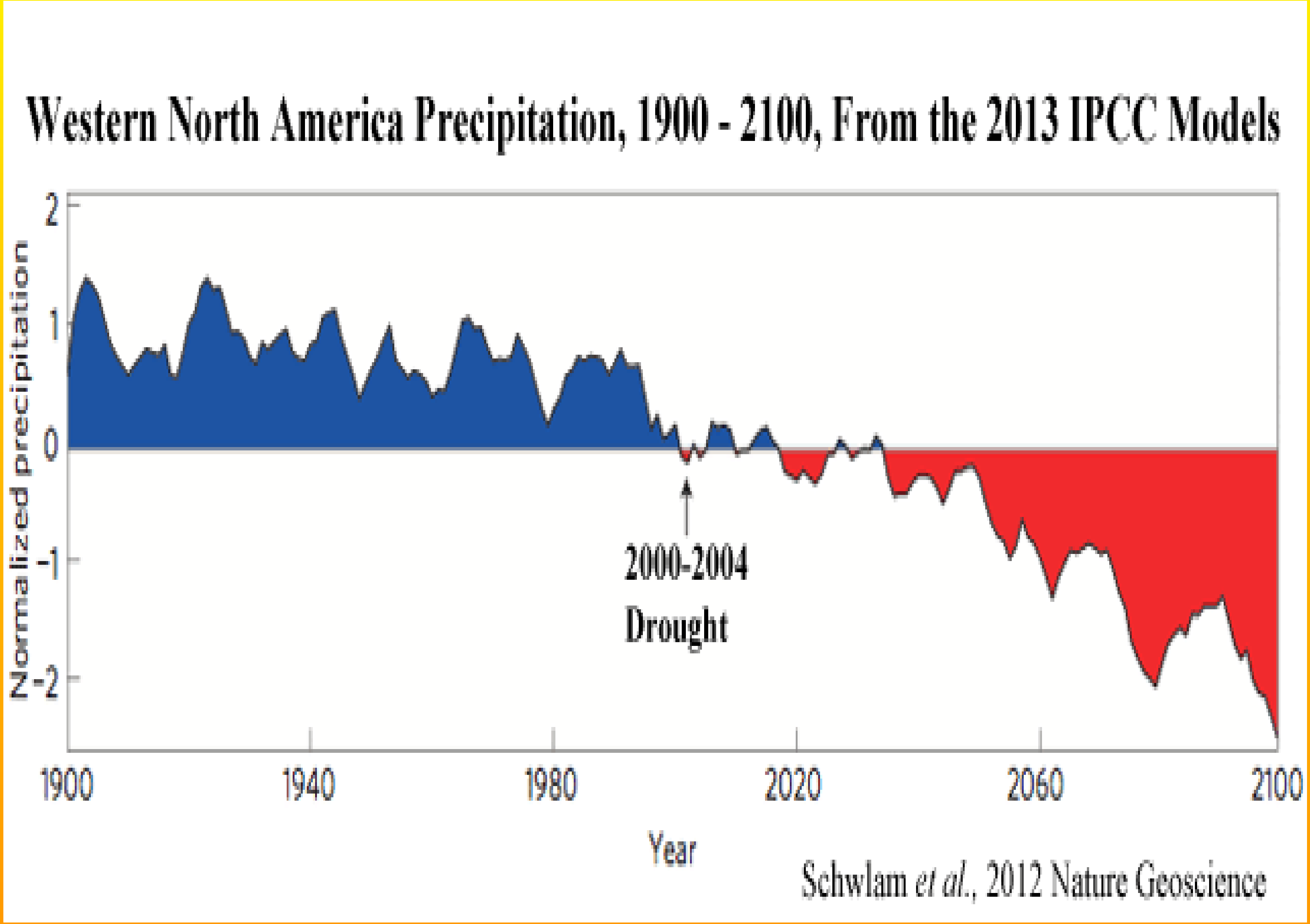
# The Five Mechanisms by Which a Warming World Accentuates Drought

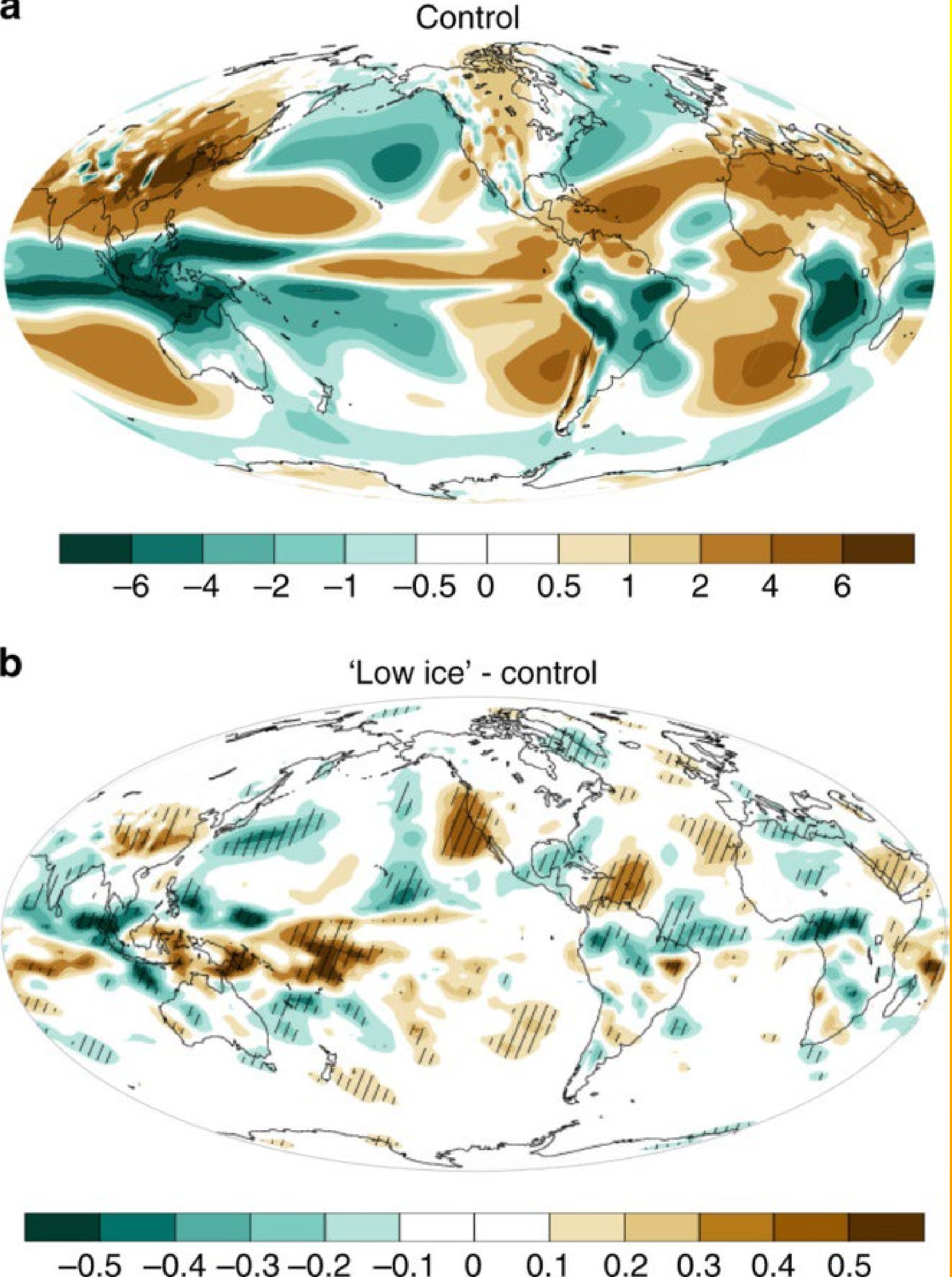
- **1.** In a warming world, a larger fraction of total precipitation falls in downpours, which means a larger fraction is lost to storm runoff (as opposed to being absorbed in soil).
- **2.** In mountain regions that are warming, as most are, a larger fraction of precipitation falls as rain rather than as snow, which means far more rapid run-off
- **3.** What snowpack there is, melts earlier in a warming world, further reducing flows later in the year.
- **4.** Where temperatures are higher, losses of water from soil and reservoirs due to evaporation are likewise higher than they would otherwise be.
- **5.** **<u>Most dominant</u>** – there is simply less precipitation of any kind, over mid-latitude lands. Increased precipitation is predicted only for the far Arctic north, and over the oceans, not where <u>people</u> actually live, which is on land.

# But There is a 6th Feedback, Which May Be Even More Dominant

- The drying of soils from existing droughts has a large damaging effect on the ability of soils to take carbon into root systems
- <u>This is a strongly amplifying biological feedback to regional greenhouse warming and drying which is not in most climate models</u>.
- **<u>Schwlam *et al.* 2012 in Nature: Geoscience</u>…**
- *"In normal climate conditions North America absorbs carbon dioxide from the atmosphere, serving as an offset to anthropogenic, or human-produced, carbon emissions," said co-author Christopher Williams, assistant professor at Clark University.* ***"Our study shows how this typical carbon uptake was severely impaired by this large-scale and persistent drought."***

# IPCC predictions of summer precip – Western U.S. droughts are just starting. Schwalm *et al.* 2012.






**Cvijanovic *et al.* 2017 confirm the link between the loss of Arctic Ocean ice and severe drought in California – note California is the worst continental land on Earth for future drought (bottom image)**

# All of these drought predictions may well be significantly too optimistic

- Climate change is predicted, and observed, to cause the northern tropical Hadley cell to expand north, bringing the desert belt at its northern edge with it.
- But observations are showing this migration is happening **3 times faster** than the IPCC models, which include no cloud feedbacks **(27:40 into this interview of cloud physicist Dr. Steven Sherwood, and Seidel *et al.* 2007**, quoting numerous studies)
- **Already, desert area is growing at the striking rate of 130,000 km$^2$/yr.**

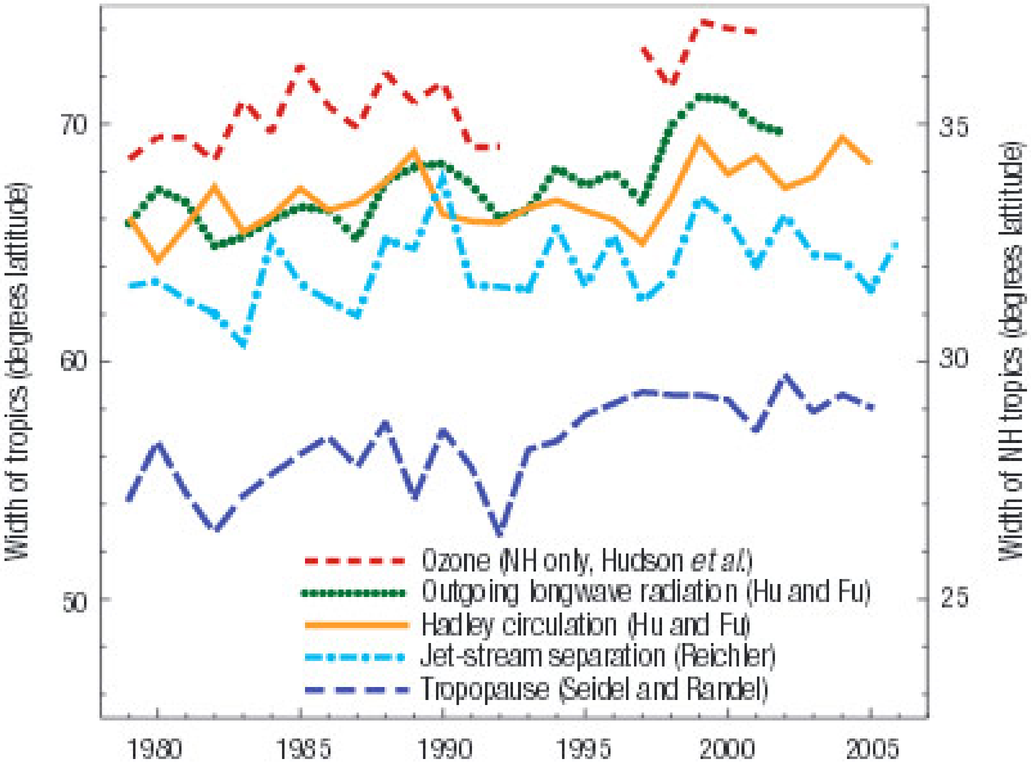



**Figure 2** Changes in several estimates of the width of the tropical belt since 1979. These include: the width of the Hadley circulation, based on both outgoing longwave radiation and horizontal winds streamfunction[10]; the separation of the Northern and Southern Hemisphere subtropical jet-stream cores; the width of the region of frequent high tropopause levels[8]; and the width of the region with tropical column ozone levels (Northern Hemisphere only, right axis, ref. 6). Although each shows an increase since 1979, the rates vary from 2.0 to 4.8 degrees latitude per 25 years, with an even larger range when considering the entire spread of trend estimates in each individual study.

**The Tropical Hadley Cell is expanding. Northward expansion of the Tropical Hadley cell boundary observed 1980 to 2005 (Seidel 2007), is much faster than climate models predicted. Central California is just over the northern border of the Tropical Hadley Cell, and so our transition into the desert climate which defines the Hadley/Ferrell border will be likely dramatic compared to most places**

**Here in Santa Cruz…**, Redwoods define the beauty of our county. But **most of the current habitat for redwoods will no longer be able to support them before the end of the century** (19:39 into this documentary, w/ studies by county scientists). **The deserts of southern California are marching northward (Seidel 2008), already by ~140 miles from 1979 to 2007**

# Stanford's Prof. Ken Caldiera, Using Climate Modelling in a RCP 8.5 Scenario…

- …finds that by year 2100, the climate of the Santa Cruz/San Jose area will be that of the dry desert and chaparral at the latitude of San Diego, and that Seattle's climate will warm and dry to become that of present day San Jose. (Petri and Caldiera 2014 in Nature)
- **This spells the end of California redwood trees**

# Other Studies: California is Losing its Majestic Large Trees

- This study in PNAS (**McIntyre *et al.* 2014**), and discussed **here**, finds that in nearly all areas of California, the great trees are dying.
- There is a 50% decline of all trees larger than 2 ft in diameter in all areas of California surveyed, except for the Central and South Coast, since 1930.
- This is due to drought, land use, and fire road cutting

# Even Sadder – The Defining Tree of California – the Giant Sequoia, Appears Doomed

- These unique trees - ***Sequoiadendron giganteum*** – sole species in their genus, are evolved to get their water by slow melting snow on the surrounding ground all spring and early summer. With snow disappearing from the California mountains, especially at the southern end of the Sierra and at their adapted altitude of ~5,500 ft, they are not expected to survive (source).
- Since 1980, total Western U.S. annual snow has dropped 40%


# Giant Sequoias – largest living things on Earth – are only found in the Southern Sierra Nevada

Sequoias require snow, especially for seedlings. Their shallow roots require water past the rainy season. But snow is becoming rarer in the Sierra…

# My Astro 28 Field Astro students, at Giant Sequoia National Monument's "Trail of 100 Giants" in 2004

**This same ~2,000 year old tree - in 2016 – fallen and dead. Some young Sequoias; dead as well (at right). President Trump hopes to open most of the monument to logging, which [this article](), in a gesture of startling understatement, calls "counter-intuitive". It reminds me of the old Vietnam War [madness]() *"We had to destroy the village in order to save it"***

# What will be the fate of these beautiful trees? Will they be clear cut before they are fully dead?

**Or will they fall to fire. In the Western U.S., the number of 1000+ acre wildfires has increased 300% since the 1970's, and the total area burned each year has gone up by 600% (source). And yet, drought is just getting started**

# Annual California Wildfire Acreage …is predicted to rise by 70% from present values, by 2050 (Jin *et al*. 2015)

# Another Iconic California Tree is Likely Doomed – the Joshua Tree

# Here: A science-based tweet from the Superintendent of Joshua Tree National Park…

- *"Current models predict the suitable habitat for Joshua trees may be reduced by 90% in the future with a* ***3°C*** *(5.4°F) increase in average temperature over the next 100 years"*
- **This comment resulted in a severe reprimand** from Trump Administration Secretary of the Interior Ryan Zinke, who insists that **climate change** is the topic *"whose name shall not be uttered"* by any National Park officials
- **This, at only +3C. Yet holding to +3C is likely impossible, when the real climate physics and paleo-data we looked at is considered, even with strong human action.**

# Other Climate Change Predictions for California

- **Dept of Interior report 2011** for western U.S.
- California – **climate model results** UC San Diego (Dettinger 2011)
- Different economic and emission scenarios share the modelling assumptions and nomenclature of the (unfortunately too conservative) IPCC, namely….

# For Reference: IPCC Nomenclature for Future Scenarios

A1 = The A1 scenarios are of a more integrated world. The A1 family of scenarios is characterized by:

- Rapid economic growth.
- A global population that reaches 9 billion in 2050 and then gradually declines.
- The quick spread of new and efficient technologies.
- A convergent world - income and way of life converge between regions. Extensive social and cultural interactions worldwide.
- There are subsets to the A1 family based on their technological emphasis:

---A1FI - An emphasis on fossil-fuels (Fossil Intensive).

---A1B - A balanced emphasis on all energy sources.

---A1T - Emphasis on non-fossil energy sources.

A2 = world economy consolidating within their regions, slower trade, no narrowing of economic gap between “haves” and “have nots”. High-income but resource-poor regions shift toward advanced post-fossil technologies (renewables or nuclear), while low-income resource-rich regions generally rely on older fossil technologies. Final energy intensities in A2 decline with a pace of 0.5 to 0.7% per year.

# IPCC “B” Scenarios – More Environmentally Friendly

**B1** = The B1 scenarios are of a world more integrated, and more ecologically friendly. The B1 scenarios are characterized by:

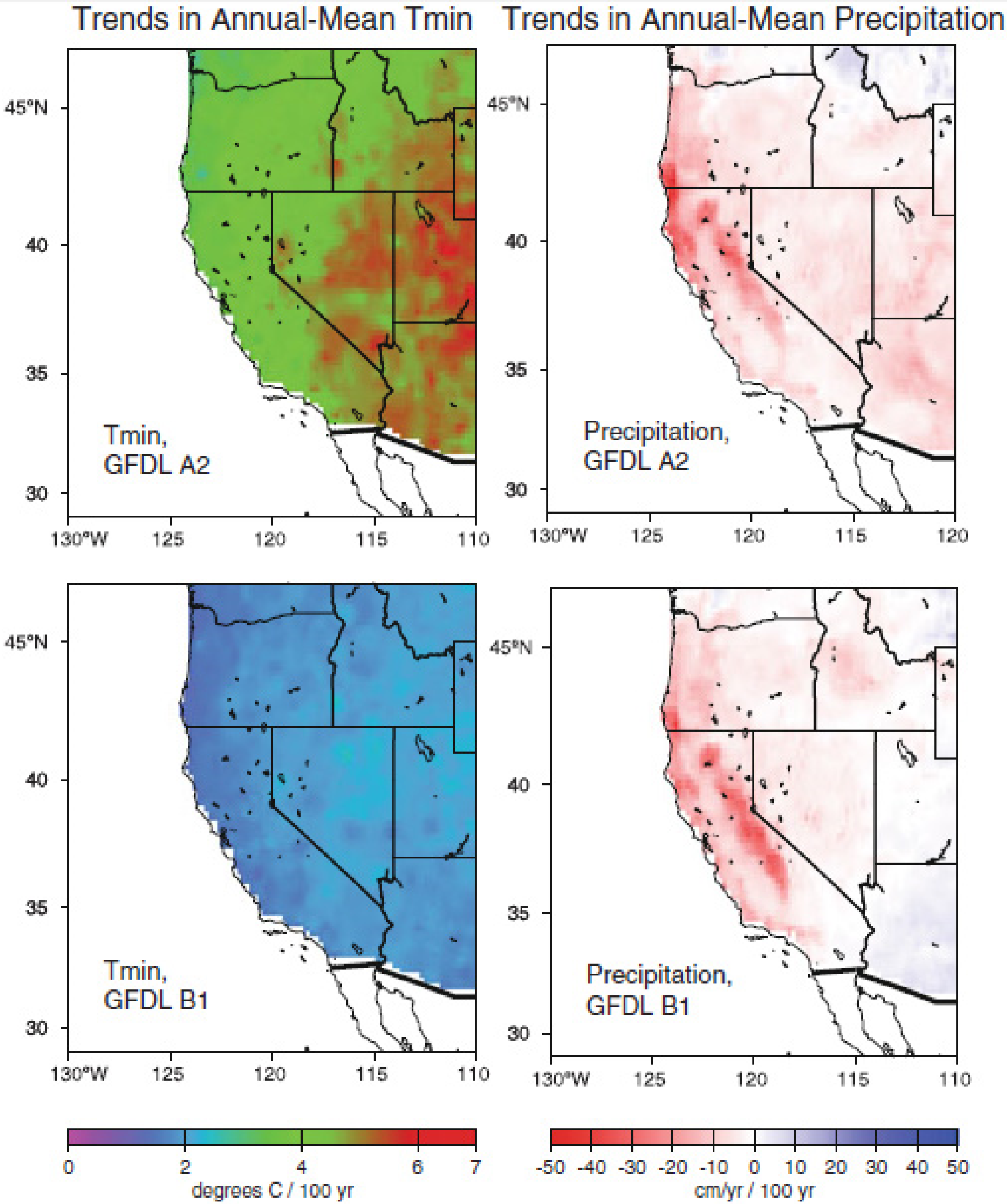
- Rapid economic growth as in A1, but with rapid changes towards a service and information economy.
- Population rising to 9 billion in 2050 and then declining as in A1.
- Reductions in material intensity and the introduction of clean and resource efficient technologies.
- An emphasis on global solutions to economic, social and environmental stability.

**B2** = The B2 scenarios are of a world more divided, but more ecologically friendly. The B2 scenarios are characterized by:

- Continuously increasing population, but at a slower rate than in A2.
- Emphasis on local rather than global solutions to economic, social and environmental stability.
- Intermediate levels of economic development.
- Less rapid and more fragmented technological change than in A1 and B1.

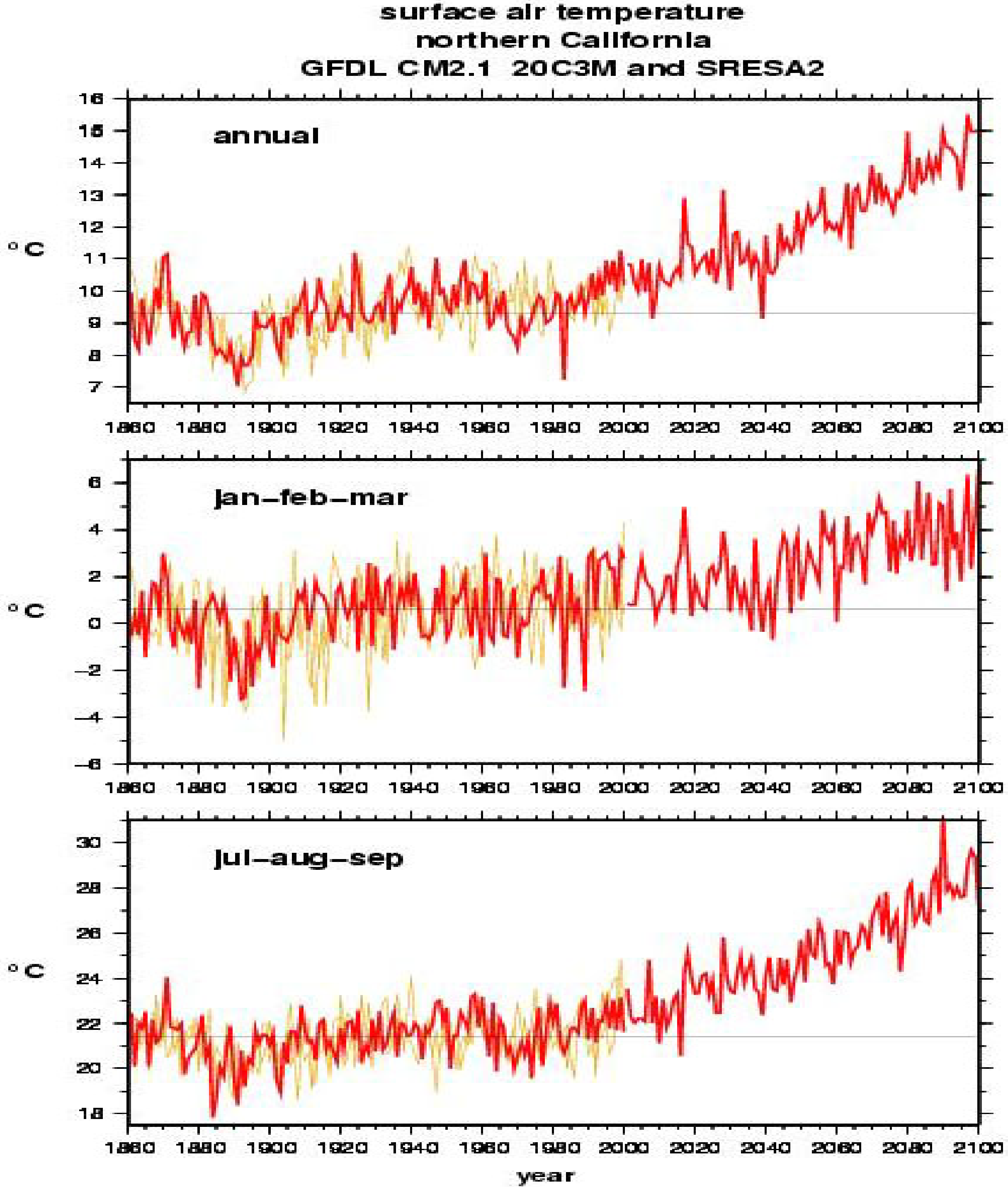
# Summary Predictions for Year 2100 from Interior Dept. Report

- Assumes “Business as Usual”
- A global temperature increase of +5 to +7 degrees C;
- A precipitation increase over the northwestern and north-central portions of the western United States **and a decrease over the southwestern and south-central areas;**
- A decrease for almost all of the April 1st Western snowpack, a standard benchmark measurement used to project river basin runoff; and
- An 8 to 20 percent decrease in average annual stream flow in several river basins, including the Colorado, the Rio Grande, and the San Joaquin (all of which are already 100% used up before reaching the ocean)
- These predictions, however, do not include the effects of methane release, the expanding Hadley Cell, newly identified amplifying feedbacks from the Arctic, and others, and are almost certainly too optimistic.




**Top two panels – A2 Scenario.** Night temps rise by 3-5C near coast, and 5-7C in desert inland. Drought areas focus on Northern California; 30-40cm/yr loss by 2100 in coastal mtns and Sierra. **Bottom two panels – B1 Scenario.** Night temps rise only 1-2C, drought still severe in Sierra, less so in northern coastal mountains *vs.* A2 scenario

(Dettinger 2011)




- **IPCC Climate Scenario A2 (Business as Usual)**
- **– Predictions for Northern California.** Annual mean, and broken up into winter, and summer months. **Summer temps rise +8C** from early 20th Century, and winter temps +3C.
- **+8C! That's over +14 Fahrenheit hotter**

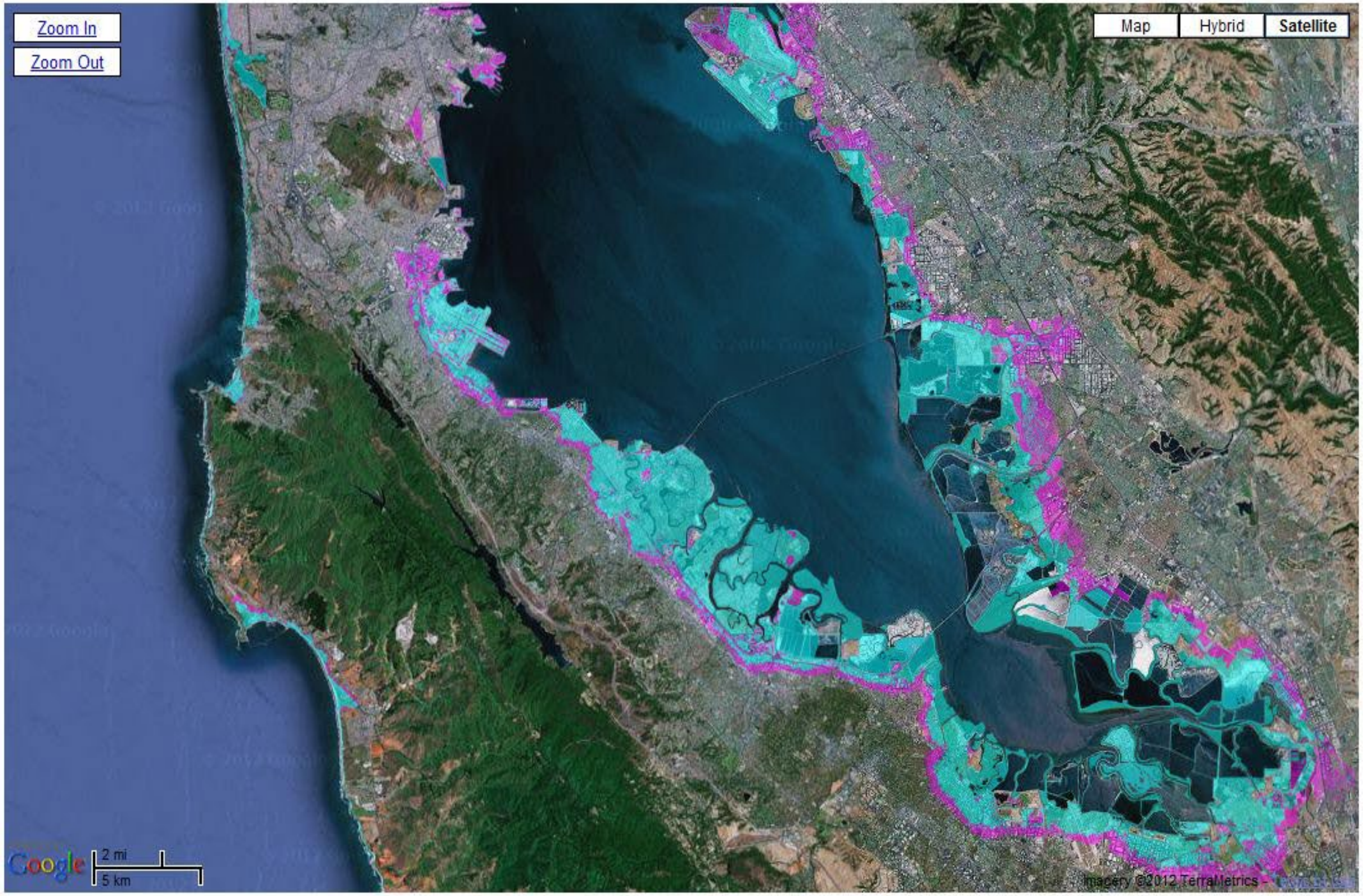
# Bay Area Sea Level Rise. Purple is +1.4m rise prediction, which is quite likely to be too conservative for 2100

## Impacts of Sea Level Rise on the California Coast

Pacific Institute

**Areas and infrastructure vulnerable to flooding and erosion**

Please see full report for assumptions, methods, and conclusions.




**Hazard Zones**

- [x] Area at risk from a 100-year coastal flood event
  - Current area at risk
  - Area at risk with a 1.4 meter sea-level rise
- [ ] Erosion
  - Area at risk from erosion in 2100 with a 1.4 meter sea-level rise
- [ ] Wetland Frontier
  - Areas where wetlands may migrate by 2100 if unimpeded

**Data Layer Opacity**

1/4 1/2 3/4 Solid

**Infrastructure at Risk**

Click map icon for details

- [ ] CA Coastal Zone
- [ ] Health-care facilities
- [ ] Schools
- [ ] Police stations
- [ ] Fire stations
- [ ] Wastewater treatment plants
- [ ] EPA-regulated sites

# West Coast Ocean Life

- Former Astro 7 “Planetary Climate Science” student Roland Saher has made an excellent film **“Climate Change Hits Home”**, on the effects of climate change affecting Santa Cruz County
- Another effect I can add, being a regular runner on the local beaches for the past 30 years… rising ocean acidification is affecting all aragonite calcium carbonate species, including mussels.

# Mussel shells are made of calcite and aragonite. Aragonite formation is becoming difficult or impossible as ocean pH drops

Santa Cruz wharf pilings, had always been packed with mussels. I'm seeing them in decline.

Instead, the beaches are (were) littered with mussel shells. Will they come back? Hard to say.

# Gravity Measurements from the GRACE Satellites…

- …shows that 1/3 of the largest aquifers in the world are in "serious distress", and are not getting replenished at anywhere near the rate they are being drained (Famiglietti *et al.* 2015, discussed **here**)
- We don't know how much of our groundwater remains. We just don't have the data at these depths.
- This is disturbing.

# El Nino / Southern Oscillation: Another Positive Feedback?

- Recent work (**Li *et al.* 2013**) building on similar work earlier, uses tree ring data and other cross-correlations with climate proxies to reconstruct the ENSO modulations of the past ~800 years
- Find that ENSO is skewing in the late 20$^{th}$ century, with the warm El Nino phase predominating over the cooler La Nina phase – perhaps due to the strong ocean heating that GHG's are delivering. The amplitude of the swing from El Nino to La Nina is more uncertain, but climate models on average show little change (**Collins *et al.* 2010**)
- Li *et al.* conclude***: "If the El Nino phase continues to become more dominant, it suggests another amplifying feedback which worsens future climate heating, and should be included in future climate modelling."***

# Underestimated IPCC AR3 projections are Still Disastrous. Observed Change is as Bad or Worse than the "Worst Case" = A2 Scenario (SRES=IPCC "Special Report on Emission Scenarios" – Both too optimistic

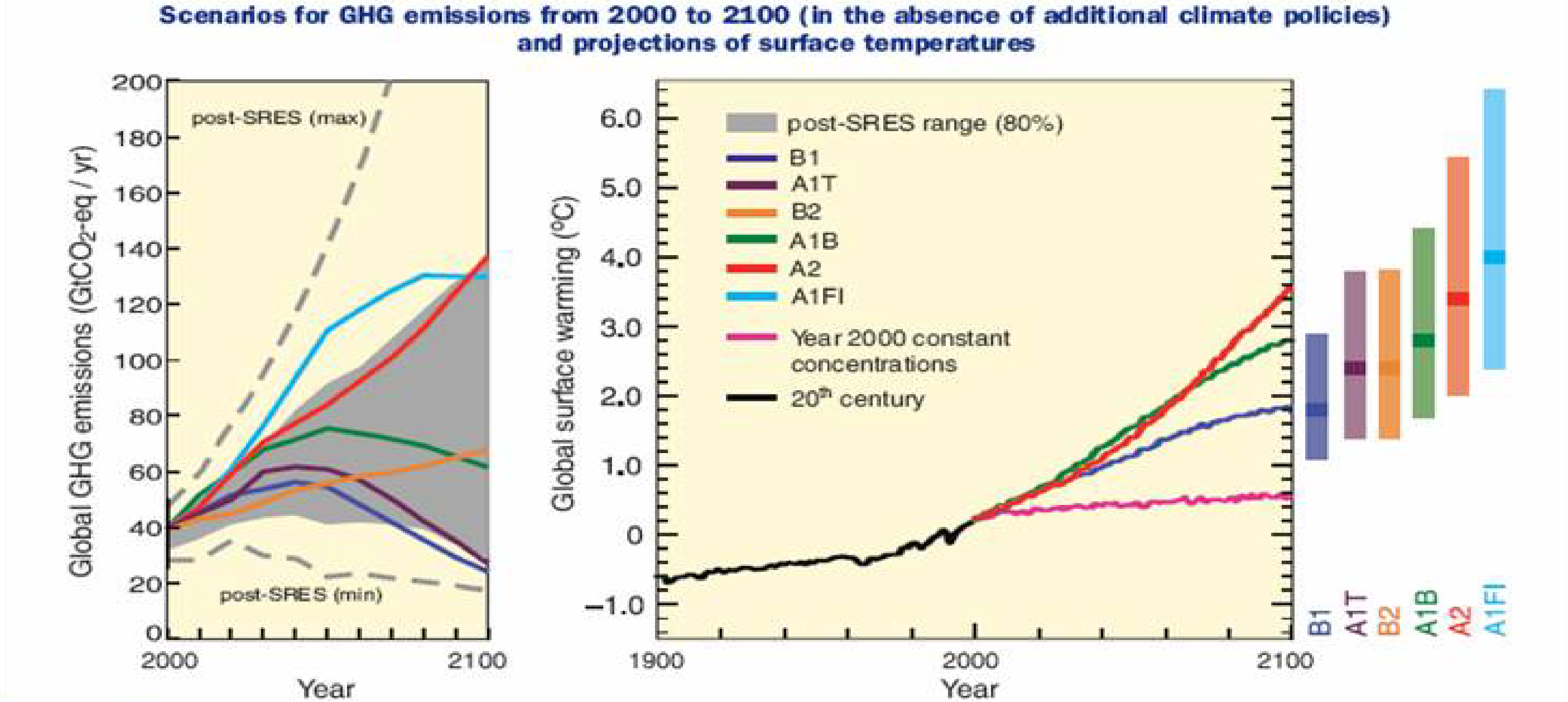



*Figure SPM.5.* **Left Panel:** *Global GHG emissions (in $GtCO_2$-eq) in the absence of climate policies: six illustrative SRES marker scenarios (coloured lines) and the 80th percentile range of recent scenarios published since SRES (post-SRES) (gray shaded area). Dashed lines show the full range of post-SRES scenarios. The emissions include $CO_2$, $CH_4$, $N_2O$ and F-gases.* **Right Panel:** *Solid lines are multi-model global averages of surface warming for scenarios A2, A1B and B1, shown as continuations of the 20th-century simulations. These projections also take into account emissions of short-lived GHGs and aerosols. The pink line is not a scenario, but is for Atmosphere-Ocean General Circulation Model (AOGCM) simulations where atmospheric concentrations are held constant at year 2000 values. The bars at the right of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090-2099. All temperatures are relative to the period 1980-1999. {Figures 3.1 and 3.2}*

# 14. The Possibilities of Societal Instability and Breakdown

# *How will Civilization Respond to this Accelerating Decay?*

- World wars have started over much less. Fighting over desires or status is one thing.... perhaps tempers can be calmed.. But fighting over basic food, water, and the very existence of, or survivability on, the land you live on, is quite another.
- <u>A +6 to +7 C global temperature rise which is now a possibility by 2100 or soon thereafter, is larger than the +5 C global temperature difference between the depths of the last great Ice Age, and our warm interglacial before human-caused global warming.</u>
- The heating of Earth will not end at 2100. Thermal forcing equilibrium is reached only after many centuries, even if CO2 levels are kept constant.
- Decarbonization of our energy might slow this, but evidence suggests we will not accomplish this fast enough to avoid all of the tipping points taking us to a new Earth System (see my other PowerPoints for more).

**Continued Business as Usual with improving fossil fuel mining technology, coal use, might eventually lead to a +12C world, as indirect human caused emissions take over. At this temperature, it would be a world in which humans in the tropics would, for the most part, die**

- *India, southern China, Pakistan, Mexico, Brazil and more, could become uninhabitably hot due to the irreversible climate change tipping points we're passing ~now or in the very near future.*
- *Do you suppose they'll simply quietly die? Or will those billions of people fight for a place in the regions still able to support human life?*
- *Even without a +12C world, the Chairman of the Global Military Advisory Council says climate refugee wars are beginning, and will get much worse (**source**), and building walls won't help.*

# India has Dam'd most of the water that now enters Pakistan

- …and as the Tibetan glaciers recede and India's population grows, it is likely there will be pressure to divert even more of that water to India, making Pakistan's already climate-challenged future worse.
- These two nuclear powers could come to war. What would just a regional nuclear war fought with just smaller Hiroshima-sized A-bombs do? Far worse than we thought: Kill ~45 million people directly, and vastly more globally due to destruction of the ozone layer, rapid climate change, and "*widespread damage to human health, agriculture, and terrestrial and aquatic ecosystems*" (**Mills *et al.* 2014**).

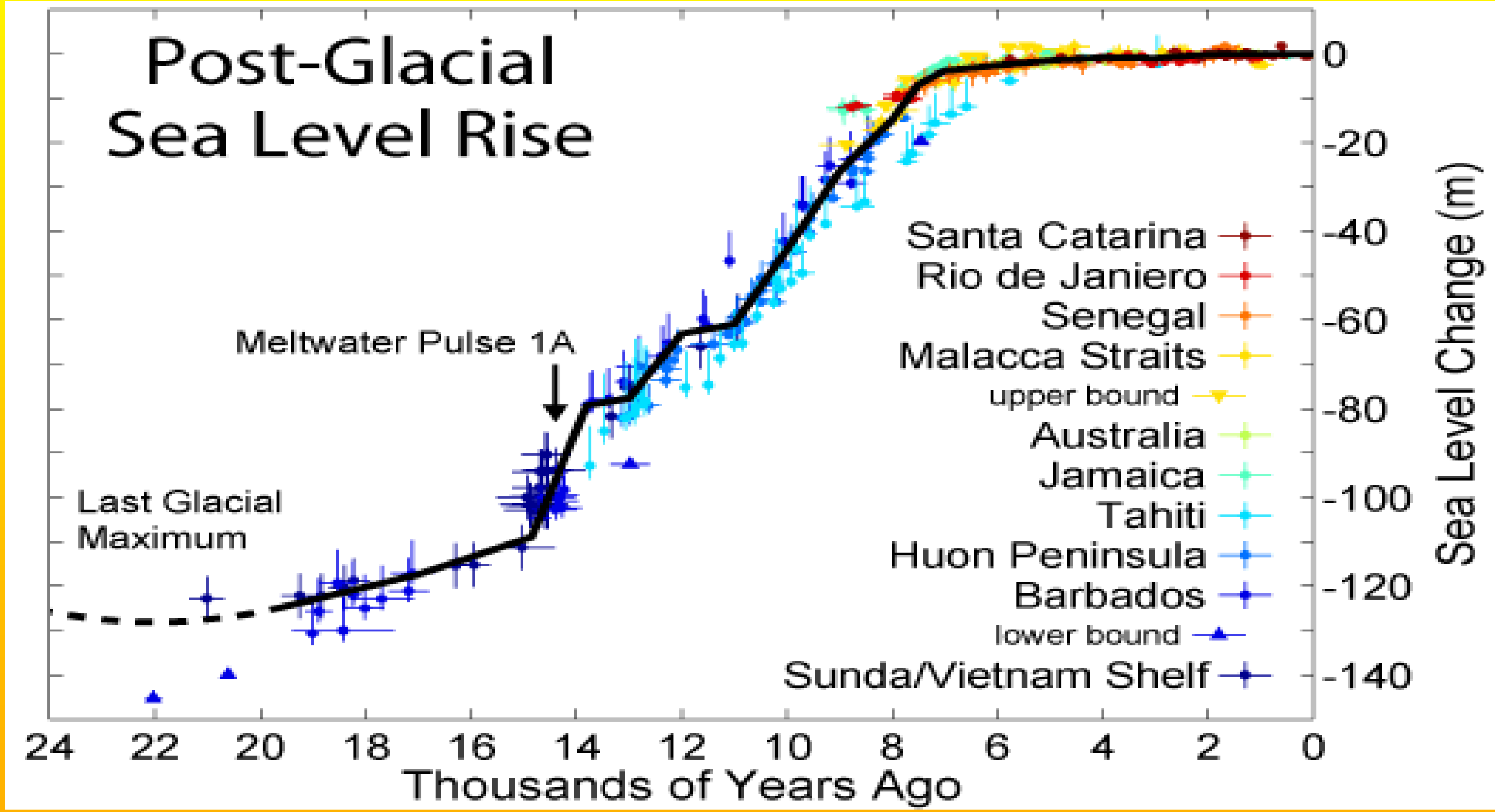
# Higher CO2 and Hotter Temperatures Linked to Variety of Psycho-pathologies

- Mental function declines by over 20% with a doubling of CO2 (**Allen *et al.* 2015**)
- Violence between individuals and groups increase significantly (meta analysis of 60 studies by **Hsiang *et al.* 2013**)
- Suicide rates increase (Burke *et al*. 2018, discussed **here**)

# Other Expectations: Continuously Flooded Ports, new "Dark Ages"

- Sea level rise in perhaps rapid pulses (*a'la* "Meltwater pulse 1A and 1B" – next slide) may make stable ports impossible
- Coastlines will be constantly changing as seas rise, for hundreds, and thousands of years. How will we re-build ports, and then re-build them again and again, and other necessary coastal facilities, without stable coastlines?
- Ecological relationships between millions of species are very complex, data very sparse and poorly understood. Outcomes highly uncertain, but not good, and so…
- A **new "Dark Ages" possible** as we grope for understanding in a world which is no longer stable and predictable, and we make mistakes in fundamental societal choices (changing farming areas, etc.), which will be much costlier in all ways than direct transitions to predictable known outcomes.

# Meltwater Pulse 1A




**Coming out of the last Ice Age about 15,000 years ago, <u>sea levels rose at a rate of 1 meter per 20 years, for 400+ years. Probably due to crumbling of the Laurentian Ice Sheet (which does not exist today).</u>**

**This was a Milankovitch (orbital change) driven warming. We're applying a climate forcing now which is <u>much</u> stronger. Will we see periods of sea level rise rate which are comparable? This is much faster than any IPCC simple melt model has in it. This had puzzled climate scientists…**

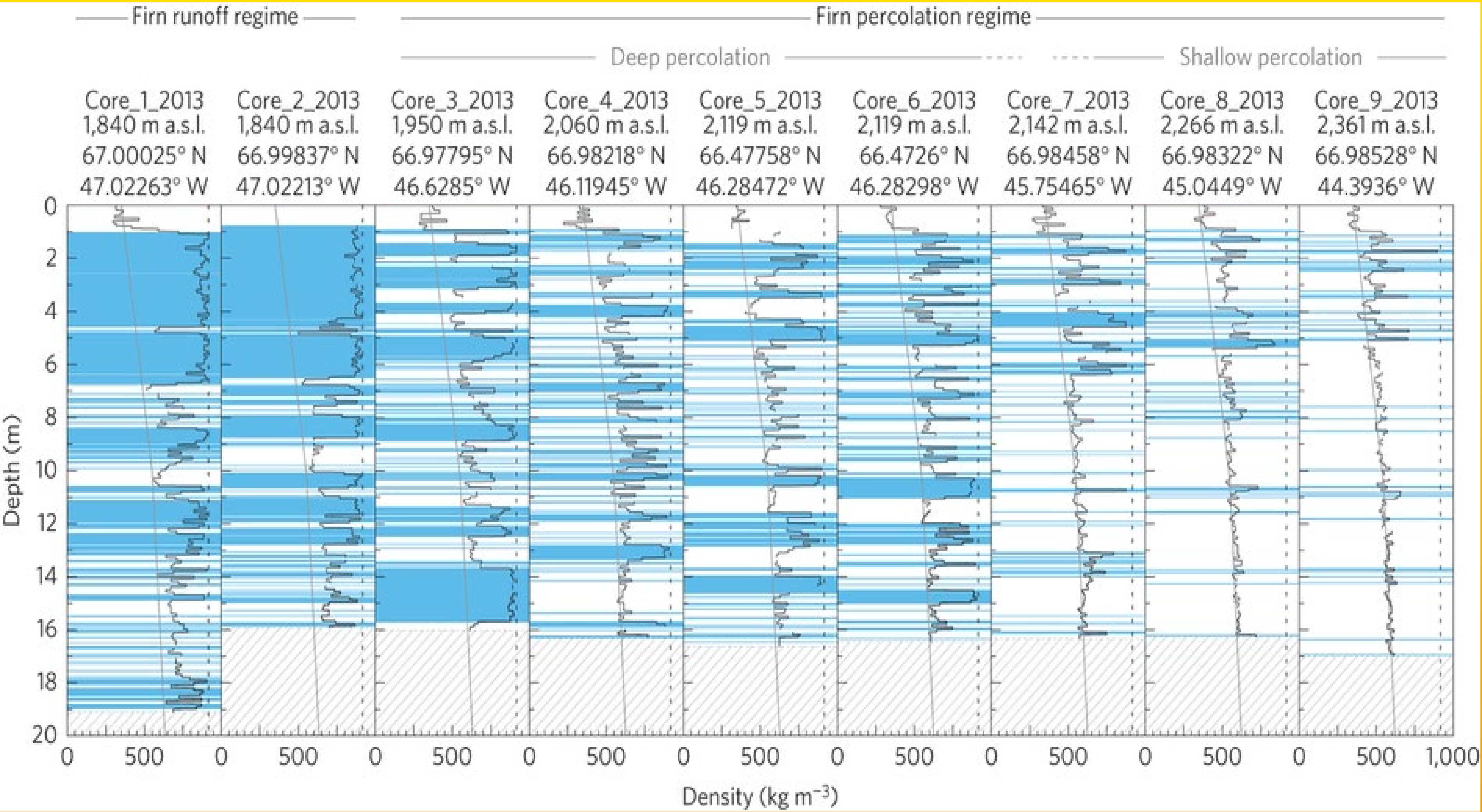
# How Can Such Weak Milankovitch Forcings Lead to Long periods of such Rapid Sea Level Rise?

- The simple models used in earlier IPCC releases did not recognize the highly non-linear rate of ice loss which is clearly seen in the paleo record.
- Hansen and Sato (2012) (linked, discussed here) argue that today's temperatures are the same as those at the tipping points of the Eemian interglacial, when sea levels rose 10-15 meters higher than today, and which dramatically amplify continental glacial loss. These include…
- Melt-through of the permanent Arctic Ocean sea ice,
- Loss of coastal buttressing of Greenland and Antarctic glaciers,
- Surface melt induced darkening the albedo of continental ice
- **Since then, all of these have begun and are rapidly accelerating, as we saw.**

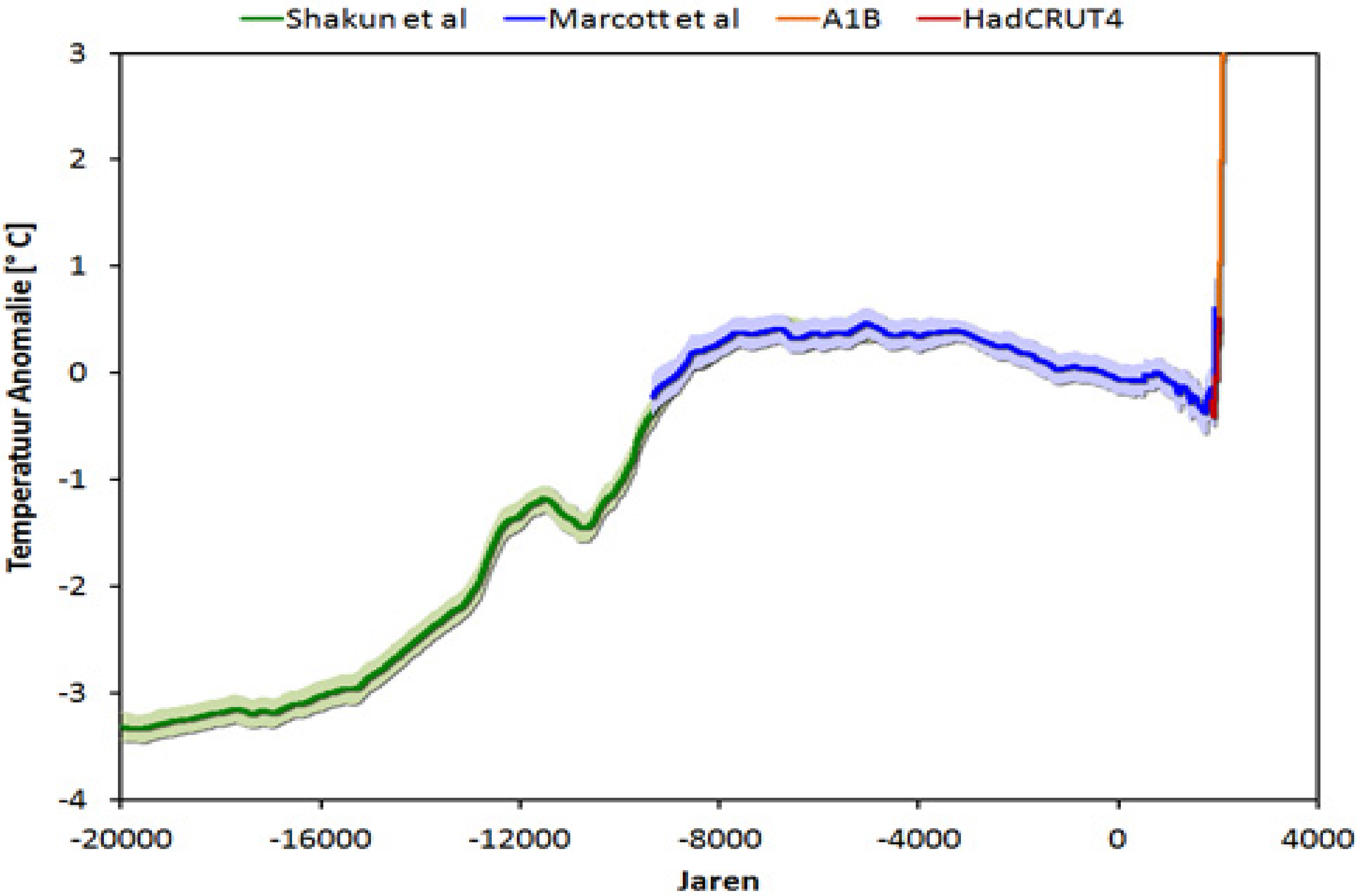
# New 2016 Study Reveals Additional Cause for Sea Level Rise

- Expectations **had** been that the "firn space" (pores within the snow pack) would provide a good storage buffer against meltwater entering the ocean, at least for a long time: surface melt would sink deep enough through firn space to re-freeze
- But not so. Machguth *et al.* 2016 (behind paywall, but good discussion is here) show that the firn space at high elevation has strongly densified already, from previous melt seasons, and at low elevation is already saturated with melt/new ice, forcing meltwater to find efficient routes off the ice sheet entirely. It also lowers the albedo of the surface, amplifying the melt further – another positive (amplifying) feedback.

From **Machguth *et al.* 2016**. Impenetrable ice lenses shown in blue, for several of their study sites on Greenland. These amplify runoff.



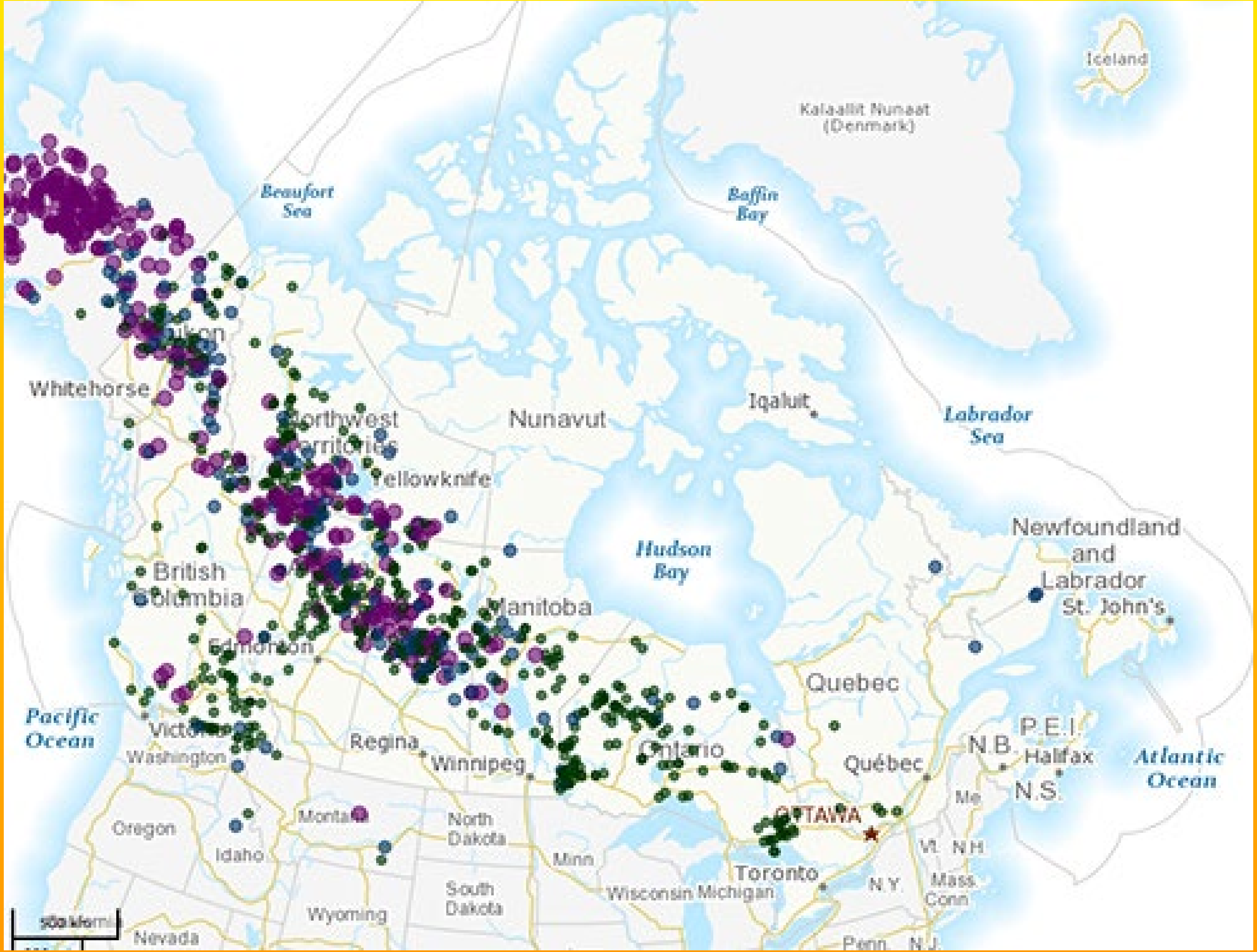
# Global Temperatures Since Depths of the Last Ice Age; Observations, and Predicted (red)



# Below is the Abstract of Hansen and Sato 2012

- *"Milankovich climate oscillations help define climate sensitivity and assess potential human-made climate effects. We conclude that Earth in the warmest interglacial periods was less than 1°C warmer than in the Holocene and that* ***<u>goals of limiting human-made warming to 2°C and CO2 to 450 ppm are prescriptions for disaster</u>****. Polar warmth in prior interglacials and the Pliocene does not imply that a significant cushion remains between today's climate and dangerous warming, rather that Earth today is poised to experience strong amplifying polar feedbacks in response to moderate additional warming****. Deglaciation, disintegration of ice sheets, is nonlinear, spurred by amplifying feedbacks****. If warming reaches a level that forces deglaciation, the* ***rate of sea level rise will depend on the doubling time for ice sheet mass loss. Gravity satellite data, although too brief to be conclusive, are consistent with a doubling time of <u>10 years</u> or less****, implying the possibility of multi-meter sea level rise* ***<u>this century</u>****. The emerging shift to accelerating ice sheet mass loss supports our conclusion that Earth's temperature has returned to at least the Holocene maximum. <u>Rapid reduction of fossil fuel emissions is required for humanity to succeed in preserving a planet resembling the one on which civilization developed."</u>*

# Climate-induced Droughts, Tree Death, and Resulting "Mega fires "(video) in the Far North Are Darkening Arctic Ice Sheets



# Annual Wildfire Burn Area in Western U.S. Growing Rapidly due to Climate Change

- Abatzoglou and Williams (2016) find that climate change has doubled the area that is experiencing wildfires, since 1984
- …and more than doubled the measures of land cover loss fuel'ed aridity.

# [Abatzoglou and Williams](#) (2016) predict that by mid century this trend will taper off…

- …there will be too few trees left to allow wildfires to propagate.

# Globally, the rainforests are being sawed and burned at staggering rates

- Pro-industry spin will have you believe that rainforest destruction is being moderated and funding to motivate saving the rainforest will have an effect.
- The reality is different: rainforest area the size of England and Wales combined is destroyed every year. 36 football fields worth **every minute**, and rising.
- At such rates, **all rainforest will be gone before 2100.** 20% of the Earth's oxygen is produced in the Amazon rainforest alone. Countries are economically motivated to cut down their rainforests as they grow only ~2%/yr at best, while the proceeds can make +10%/yr in the stock market (see **here**)
- This will alter climate, global liveability in profound ways.

**Those responsible can even collect money from REDD - the program supposedly designed to <u>reduce</u> rainforest logging. How? By planting trees – industrial palm oil trees (below on clear-cut rainforest land). [Corruption is rampant](), and [organized crime]() is in the carbon-trading market.**

**In a fitting twist of Fate, the Alberta tar sands boom town Fort MacMurray area was "wiped clean by the wrath of God" by firestorms enabled by climate-induced drought and tree death in May '16**

The **Alberta Firestorm** from ~10 miles away. Flames spiral over a mile into the sky

# Entire City of Fort McMurray Evac'd

A fleeing resident on cell phone: *"It's like Arma-geddon here!"*

# A New Discovery Might Play Some Future Role As Well…

- CO2 has been discovered to have a corrosive effect on ice. It breaks the hydrogen bonds of water. (Buehler *et al.* in Journal of Physics D: Applied Physics 2013 and summarized here)
- This is seen at the microscopic level, and how it may affect ice on a large scale isn't yet known.
- $CO_2$ concentrations have now risen 50% since pre-industrial times, likely increasing this corrosive effect.
- However, my guess is that this is a minor effect, since it is not significantly non-linear.

**Most Plants are primarily nitrogen-limited. However, there are a few plant species which are more carbon-sensitive and will do preferentially well in the coming world. This is especially true of *poison oak*, whose growth rate doubles with just a 25% increase in $CO_2$, and whose oily urisol transforms into a more intense form (source)**

# And Some Local Anecdotal Evidence

- I regularly run on trails through the mountains here in Santa Cruz, and I’m seeing poison oak growing at rates I’ve not seen before, covering trails I used to run without worry
- It’s overtaking parts of Cabrillo College Observatory and, in desperation, I bought and sprayed a whole quart of *Round-Up* on it (Sorry! This was before the 2016 cancer studies were published)… **to no effect whatsoever**.
- The local poison oak continues to expand.

**New studies also find that spiders will get bigger and faster. So arachnaphobes will have that to look forward to as well. And…**

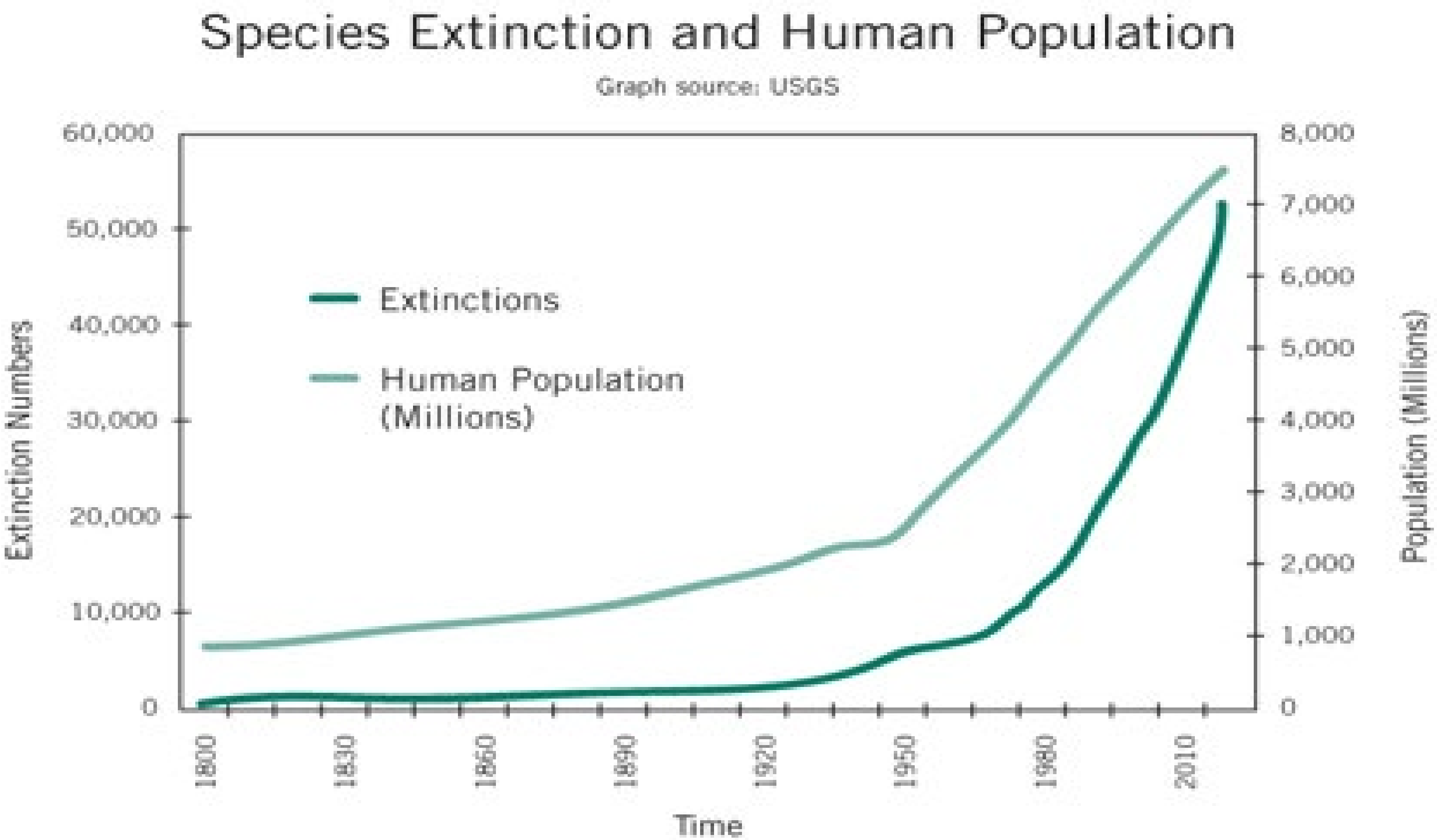
# “SuperNests” Generating Hordes of Yellow Jacket Wasps


Warmer winter temperatures are not allowing nests to **reset**. *“So normally, a surviving queen will have to start a colony from scratch in the spring. With our climate becoming warmer, there might be multiple surviving queens producing more than 20,000 eggs each.”*

# Evolution and Adaptation?

- It can be done… but only when there is TIME to evolve. **We don’t have that time**…
- The time scale problem and thermal inertia means strong climate action change must happen long before the most severe consequences manifest.
- **Rapid change, whether by asteroid impact, or rapid climate change, means extinctions. This is the message of the paleo record**
- **”Has the Earth’s Sixth Mass Exctinction Already Arrived?” Barnofsky *et al.* (2011) Nature vol. 471) and mass extinction in the oceans here**

Correlation **is** causation, in this case. **Species extinction rates are accelerating much more rapidly even than human population. This graph is only the last 200 years**



# The Top Cause of Today's Extinctions: Over-exploitation of the Environment by Humans.

- Climate change currently ranks only 7th on the list of causes, according to **Maxwell (2016)** discussed **here**.
- However, that ranking should rise rapidly as climate change ramps up from here.

# Rising Extinctions, now ~50 times normal background rate

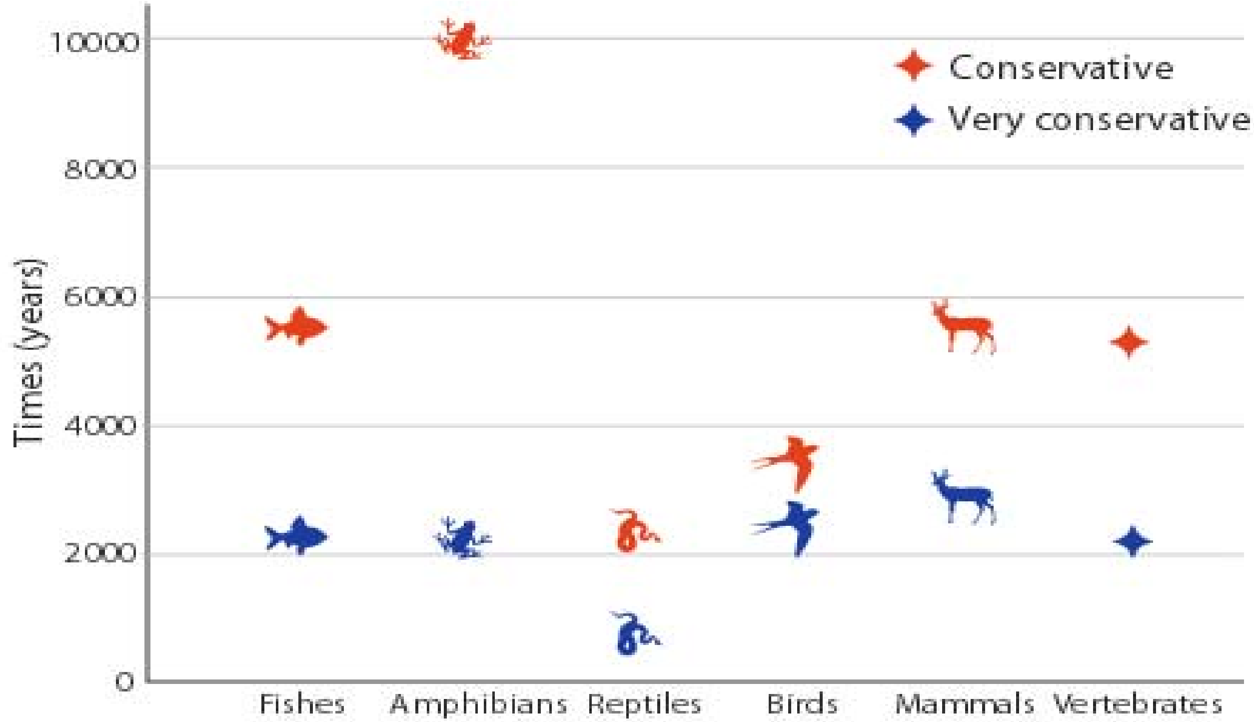
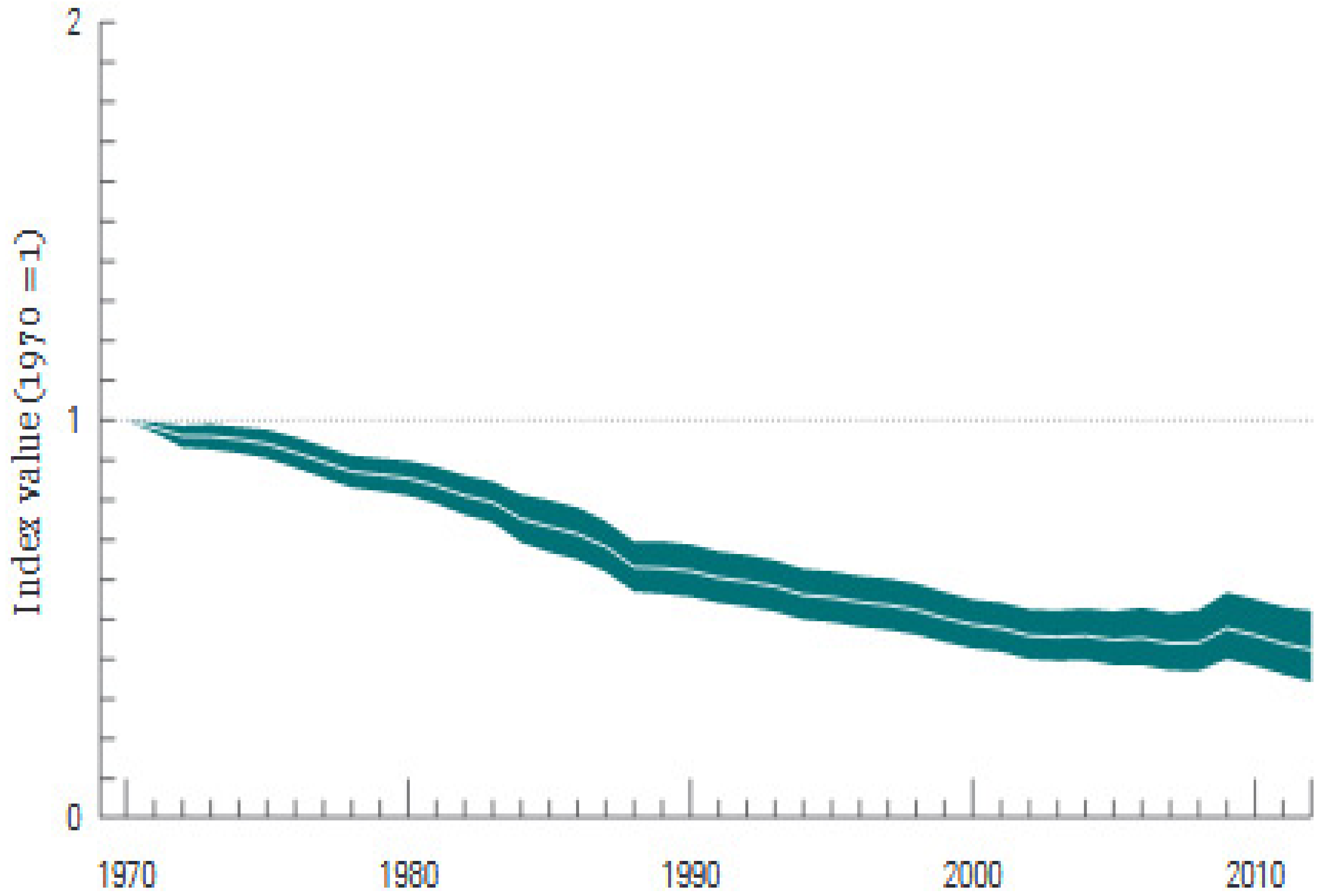



**Fig. 2. Number of years that would have been required for the observed vertebrate species extinctions in the last 114 years to occur under a background rate of 2 E/MSY.** Red markers, highly conservative scenario; blue markers, conservative scenario. Note that for all vertebrates, the observed extinctions would have taken between 800 to 10,000 years to disappear, assuming 2 E/MSY. Different classes of vertebrates all show qualitatively similar trends.

- Thomas *et al* (2004) using the relatively mild scenarios of the early IPCC models, find 15-37% of all Earth's species will be "committed to extinction" by 2050.
- Other studies find more like 50% of all species will be extinct by mid-century.
- But extinction rate estimates are mostly done by computer modelling and are highly controversial.
- Documenting true extinction is very difficult and expensive, so the data remain uncertain. A better measure is the **Living Planet Index**, which is a biodiversity measure: a convolution of species number and of species population.

**The Global Living Planet Index, a measure of biodiversity and species abundance, dropped 58% for vertebrates (3,706 species) from 1970 to 2012, dropping at a consistent 2% per year (the "Great Recession" of '08 momentarily helped non-human species). If continued, this would imply the majority of Earth's species will be gone by century end.**

***Figure 2: The Global Living Planet Index shows a decline of 58 per cent (range: -48 to -66 per cent) between 1970 and 2012***
*Trend in population abundance for 14,152 populations of 3,706 species monitored across the globe between 1970 and 2012. The white line shows the index values and the shaded areas represent the 95 per cent confidence limits surrounding the trend (WWF/ZSL, 2016).*



# Freshwater species even worse: 81% decline since 1970

figures are based on data for 3,324 monitored populations of 881 freshwater species.

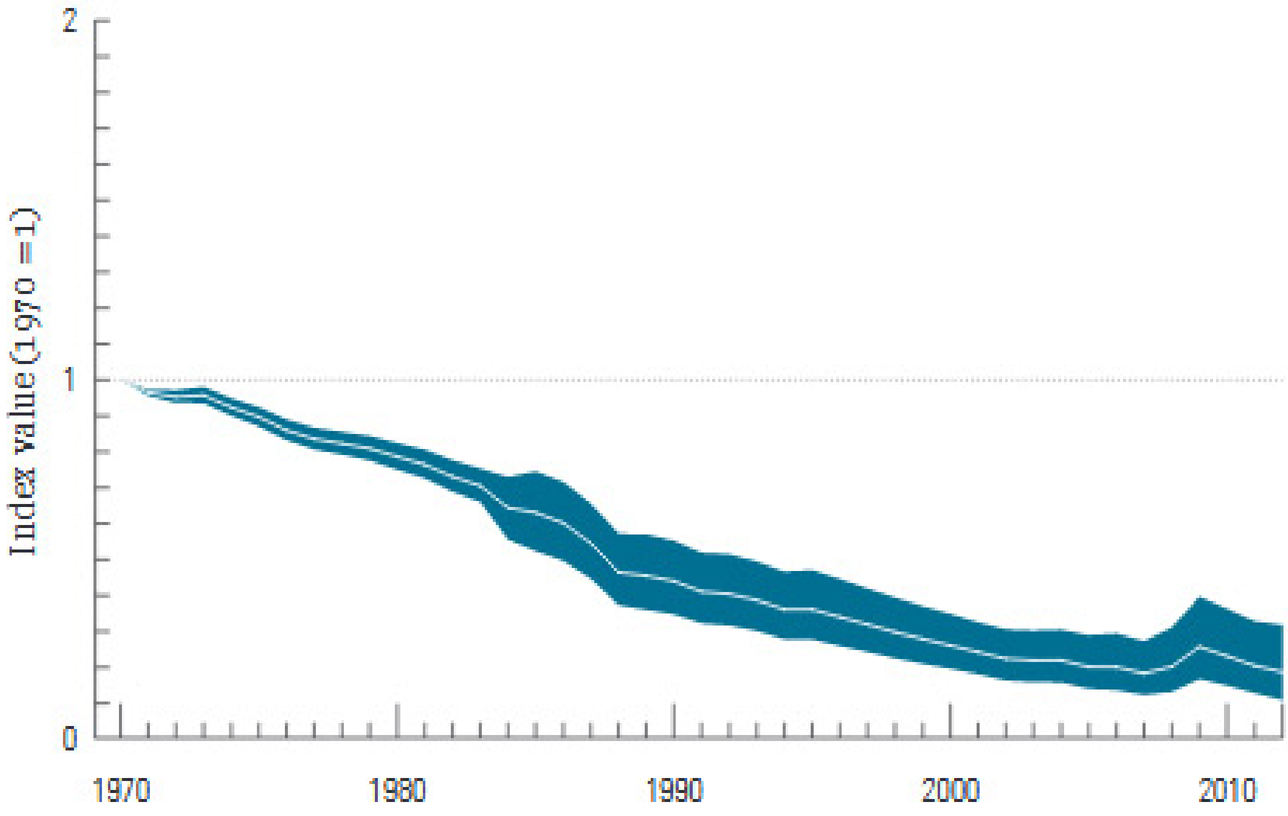
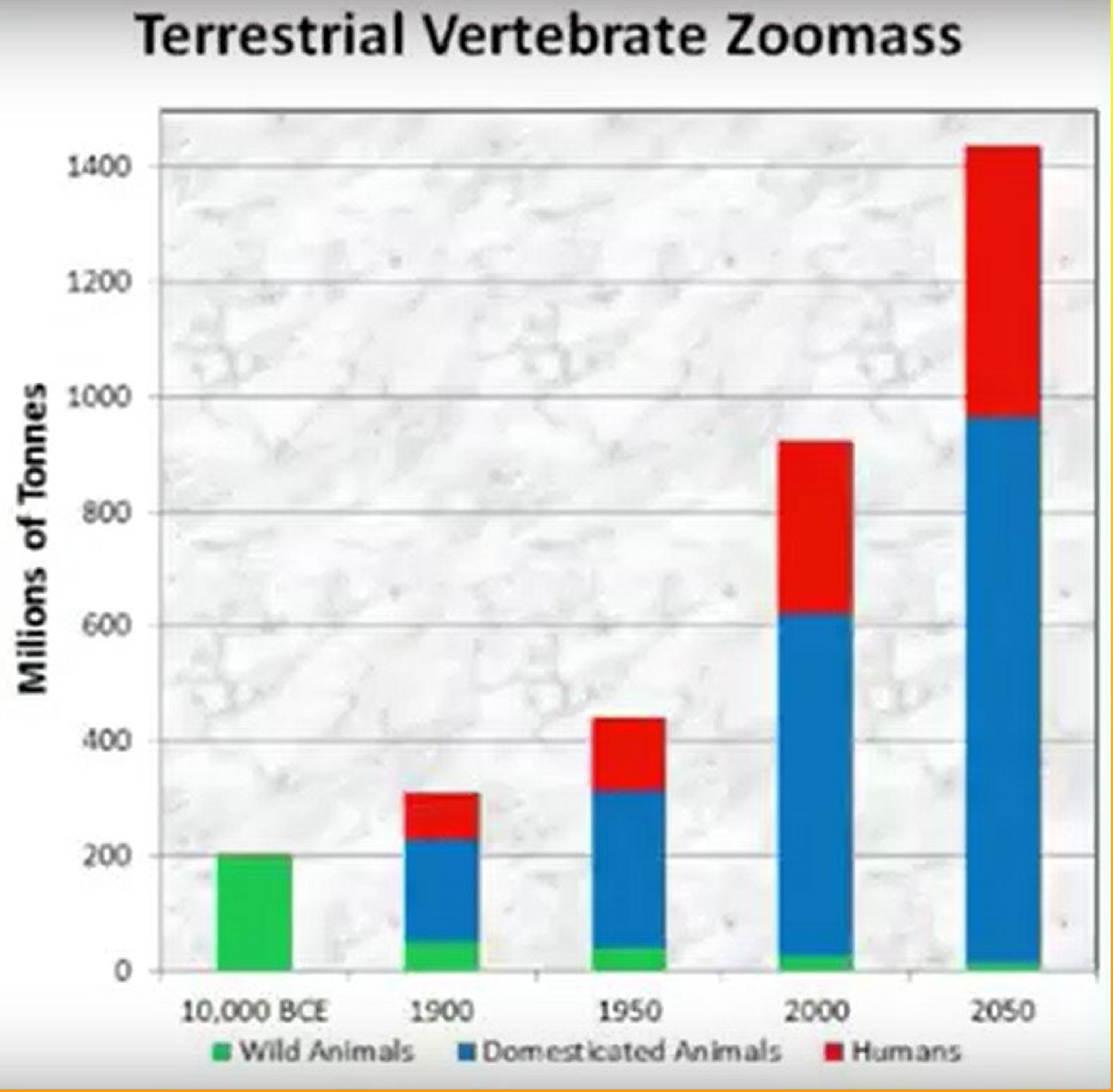



***Figure 12: The freshwater LPI shows a decline of 81 per cent (range: -68 to -89 per cent) between 1970 and 2012***
*Trend in population abundance for 3,324 populations of 881 freshwater species monitored across the globe between 1970 and 2012 (WWF/ZSL, 2016).*

*Key*

Freshwater Living Planet Index

Confidence limits




**Humans (red) and their livestock (blue) have eliminated most wild animals (green) from Planet Earth**

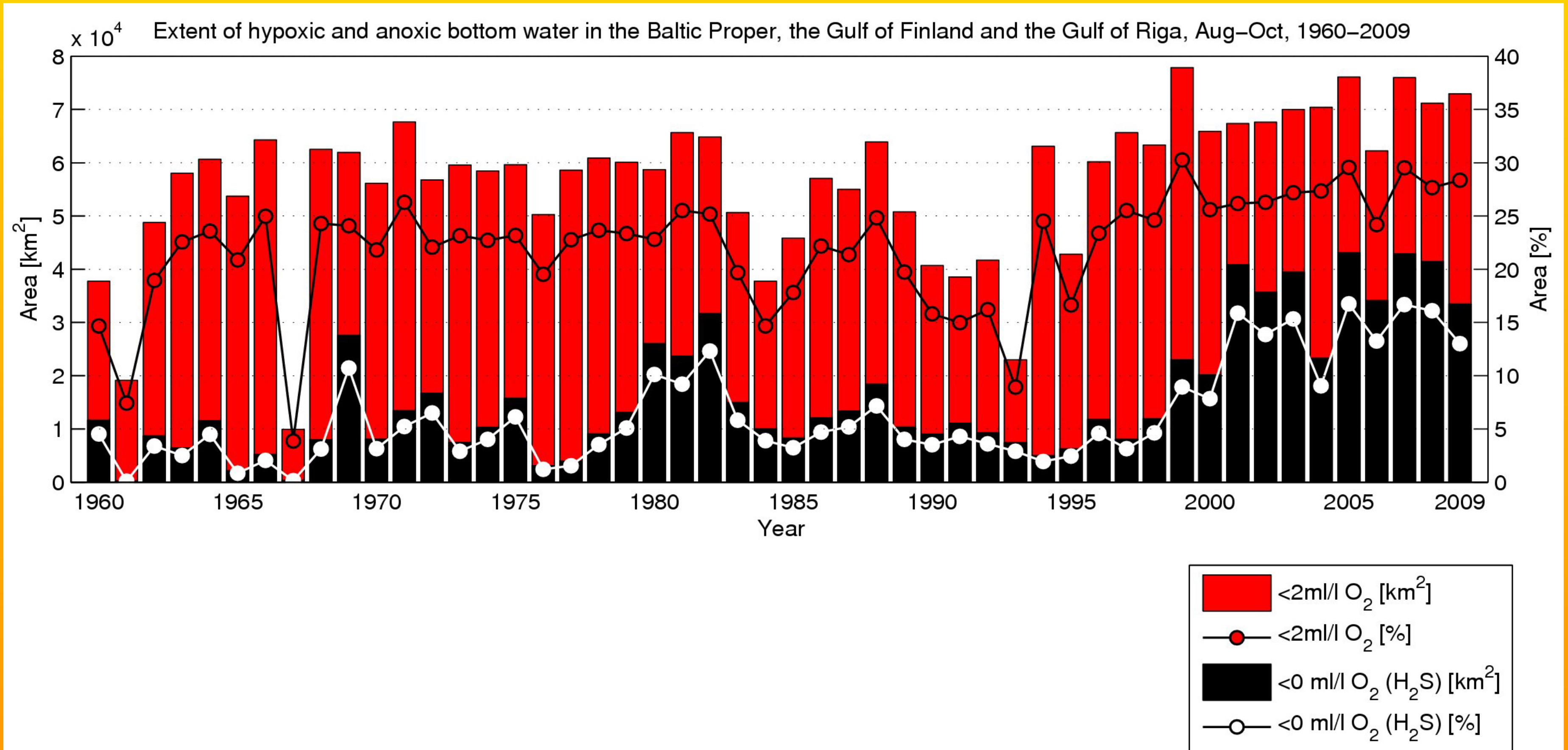
# The End Permian Extinction: caused by fossil fuel burning

- Not by humans, obviously (252 million years ago). But large volcanism in Siberia is now known to have set afire coal deposits and the rapid rise of CO2 caused rapid climate change.
- As temperatures rose, oxygen declined, leading to dead zones in the oceans, ocean acidification, and worst of all - a shutdown of the ocean circulation, causing rapid oxygen depletion and leading to deadly $H_2S$ formation in the anoxic ocean bottom. This rose to the surface. This may be one of the killing agents for this extinction.
- Note the parallels with our present and near future.

# Paleontologist Peter Ward argues the evidence supports that ocean anoxia and resulting $H_2S$ may be the killing mechanism of the CO2-induced Paleo mass extinctions

- Polar amplified heating causes shutdown of ocean currents, leading to stagnant surface waters and stratification, leading to a starvation of oxygen in deeper layers, initiating the creating of deadly hydrogen sulfide by anaerobic bacteria, which then snuffs out life above and below the ocean surface. (video lecture **here**).
- Today, the slowdown of the AMOC, he argues, may be the beginning of this same process in our future.

# Today, anoxic events are rising worldwide; below, in the Baltic Sea, but also in the Gulf of Mexico and elsewhere



# Climate Rate of Change, and Extinctions

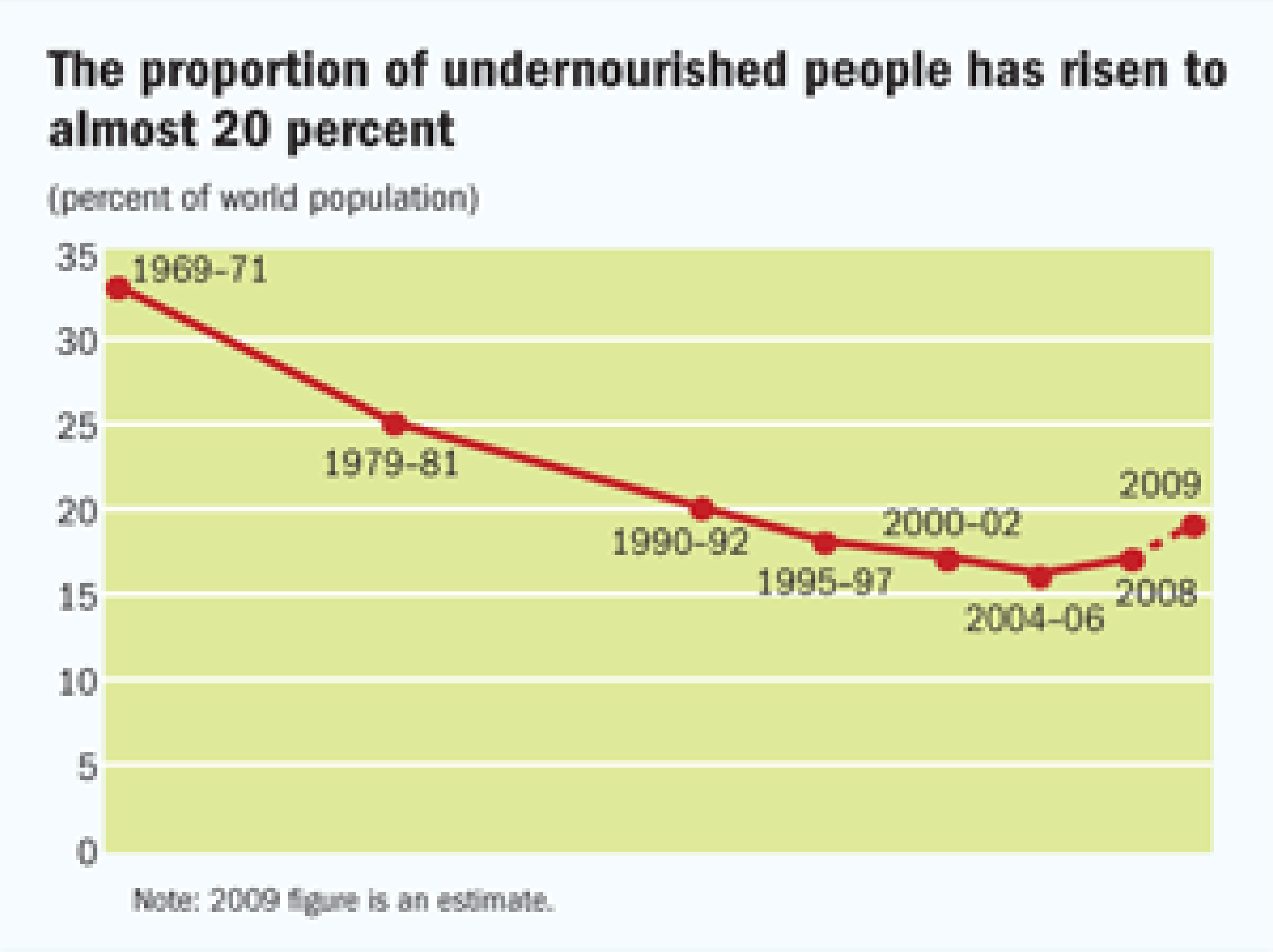
- It is rapid CHANGE that causes extinctions – rapid beyond the ability of species to adapt to.
- *“The rate at which we’re injecting $CO_2$ into the atmosphere today, according to our best estimates, is 10 times faster than it was during the End-Permian,” the paleoclimatologist Lee Kump, dean of the College of Earth and Mineral Sciences at Penn State, told me. “And rates matter. So today we’re creating a very difficult environment for life to adapt, and* ***we’re imposing that change ~10 times faster than the worst event in Earth’s history.”*** **(source)**

# The Carrying Capacity of Earth - Reducing Population

- Burning through, in a couple hundred years, the Earth's accessible store of fossil fuels - an inheritance which took a hundred million years to create, is symptom of a larger problem. We on Earth have been living far beyond the ability of the planet to sustainably support.
- **Humans and our domesticated livestock have gone from being 0.1% of the biomass of all land vertebrates 10,000 years ago to 50% just 100 yrs ago, to now being 97%.**
- We're **losing 1% of the Earth's topsoil every year**, due to **typical agriculture practices**. At current rates **it could be gone in 60 years**.Topsoil is irreplaceable on human civilization time scales.
- World population is projected to reach 9.5 billion by mid-century. We went from 7 to 8 billion in just 13 years.
- Our planet can, with current technology, support this many people sustainably only at a standard of living equivalent to ~2010 **Ethiopia**, according to a number of studies at Stanford University (links **here** and **here**).


Ethiopia has one of the harsher standards of living on Earth, and is [near the bottom of the 2015 UN Happiness Index] rankings of countries (see ~20% of the way down this longer link on the happiness of Scandinavian countries)

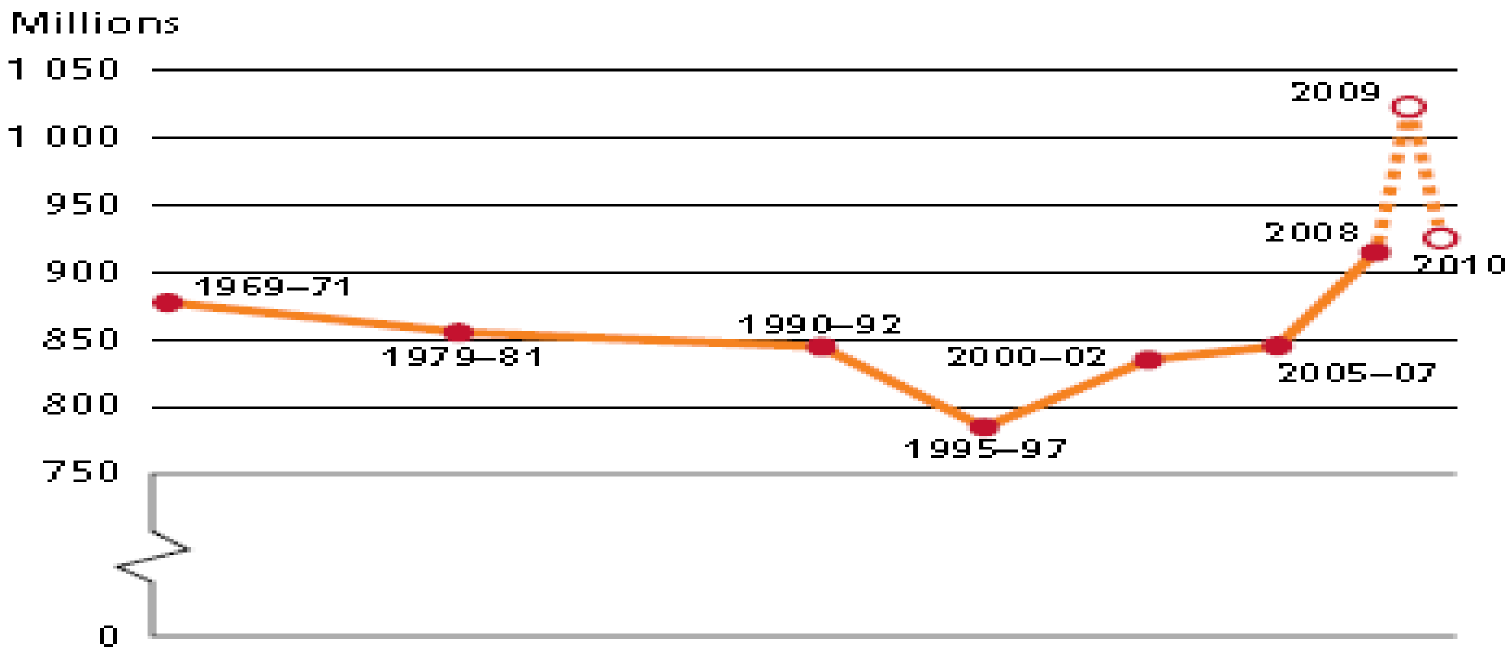
# As the "Green Revolution" falls behind, due to climate change damaged soils, shifting growth zones, and loss of topsoil, famine is now on the rise in the 21st Century



**Inevitable food price hikes devastate poorer countries, leading to riots and revolutions. Expect the trend to accelerate as drier soils hurt nitrogen fixation, and if the "Green Revolution" continues to fall behind. Nett *et al.* 2016 finds climate change directly promotes rising terrorism. Expect it to accelerate.**

FIGURE 1

Number of undernourished people in the world, 1969–71 to 2010




Note: Figures for 2009 and 2010 are estimated by FAO with input from the United States Department of Agriculture, Economic Research Service. Full details of the methodology are provided in the technical background notes (available at www.fao.org/publications/sofi/en/).

Source: FAO.

# How Does Economic Civilization Do in a +4C World in year 2100?

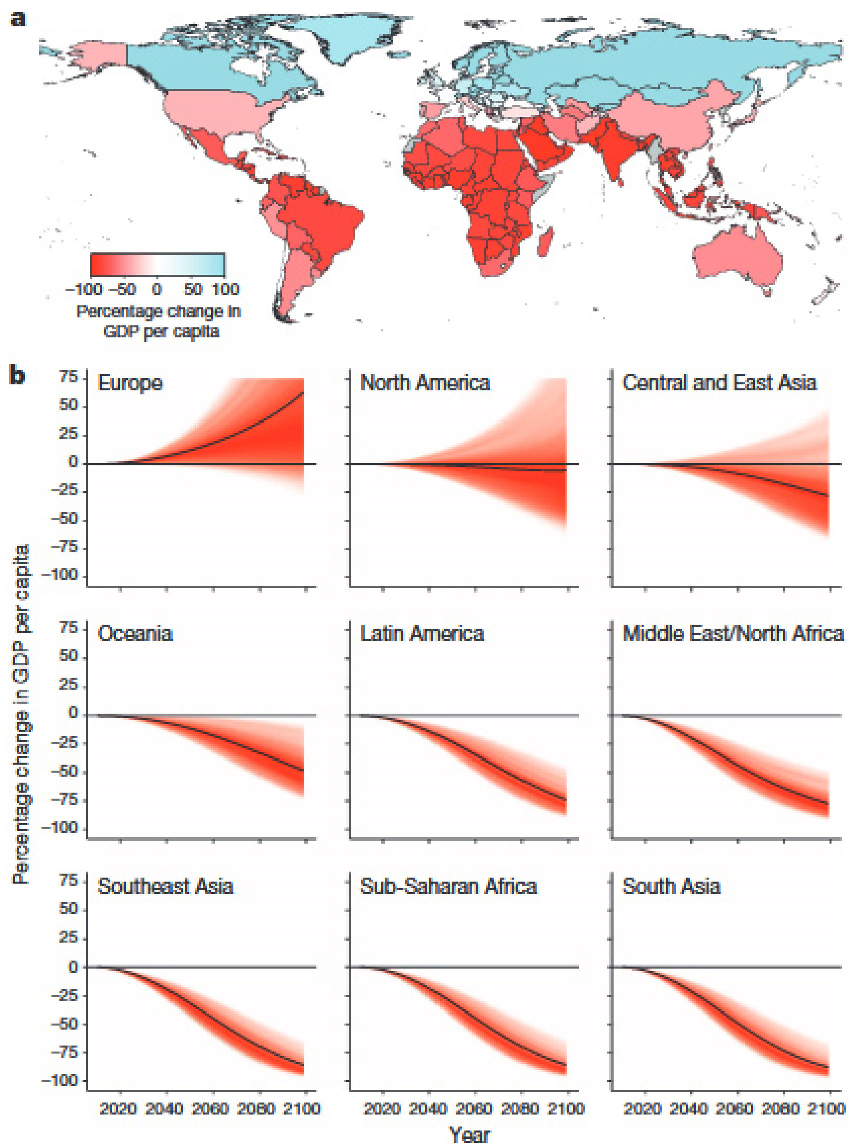



**Figure 4 | Projected effect of temperature changes on regional economies.** **a, b,** Change in GDP per capita (RCP8.5, SSP5) relative to projection using constant 1980–2010 average temperatures. **a,** Country-level estimates in 2100. **b,** Effects over time for nine regions. Black lines are projections using point estimates. Red shaded area is 95% confidence interval, colour saturation indicates estimated likelihood an income trajectory passes through a value[27]. Base maps by ESRI.

Stanford studies [(Burke *et al.* 2015](#)) used historical data and IPCC RCP 8.5 temperatures at 2100 (+4C) to find that **GDP per capita plummets by ~70-80% (and still falling) by 2100 for essentially the entire Tropics:** Africa, Southern Asia, South America, Central America.

# However, this study does not consider damaged global trade from flooding ports, nor the immigration wars which will result from economic collapse.

- **It is also not clear whether they mean annual GDP growth drops by ~70% i.e. 2% annual GDP growth becomes 0.6% annual GDP growth, which is unrealistically optimistic, or whether the absolute GDP drops from $X dollars per year to [0.3]x $X dollars per year. That would seem far more realistic (and more in keeping with the literal reading of the y-axis), given climate science knowledge. My attempts to contact the author were not answered.**
- Russia is the biggest winner, and we are seeing their predictable reaction to global warming.
- Now consider **This article** discussing the incredible belief of conservative economist William Nordhaus (father of the original ***"+2C is a good, safe compromise"*** **back in '75) that a "+4C world is optimal".**
- **It's unbelievably climate-naïve, and a claim more horrifically damaging to our climate future than I have ever encountered from any academic; indeed, from any responsible person**. More on this **here**.

# Now Consider This Article…

…discussing the incredible belief of Neoclassical economist William Nordhaus (father of the original ***"+2C is a good, safe compromise"* back in '1975)** that now a *"+4C world is optimal"*.

It is unbelievably climate-naïve, and a claim more horrifically damaging to our climate future than any I have ever encountered from any academic; indeed, from any responsible person. More **here**.

# Expect Walls to Go Up, Protecting Against the Hordes of Migrants Fleeing the Tropics

- **It's already begun**. Rising temperatures and **drought have killed 80% of the maize crop** in Honduras and Guatamala, a major cause of the migrant waves seeking asylum in the U.S. in 2019.

# Migrants and their Children Face Tragedy at the Border

When fear of the future rises, people often sanction brutality, desperate to hang on to what they still have. Without drastic change, expect this to accelerate.

**So… A future world dominated by stinging jellyfish in the oceans, and on land by super-charged hard-to-kill poison oak, tripled growth rate of weeds *vs.* crops, rising drought, rising resource wars, terrorism, and resulting plummeting economies**

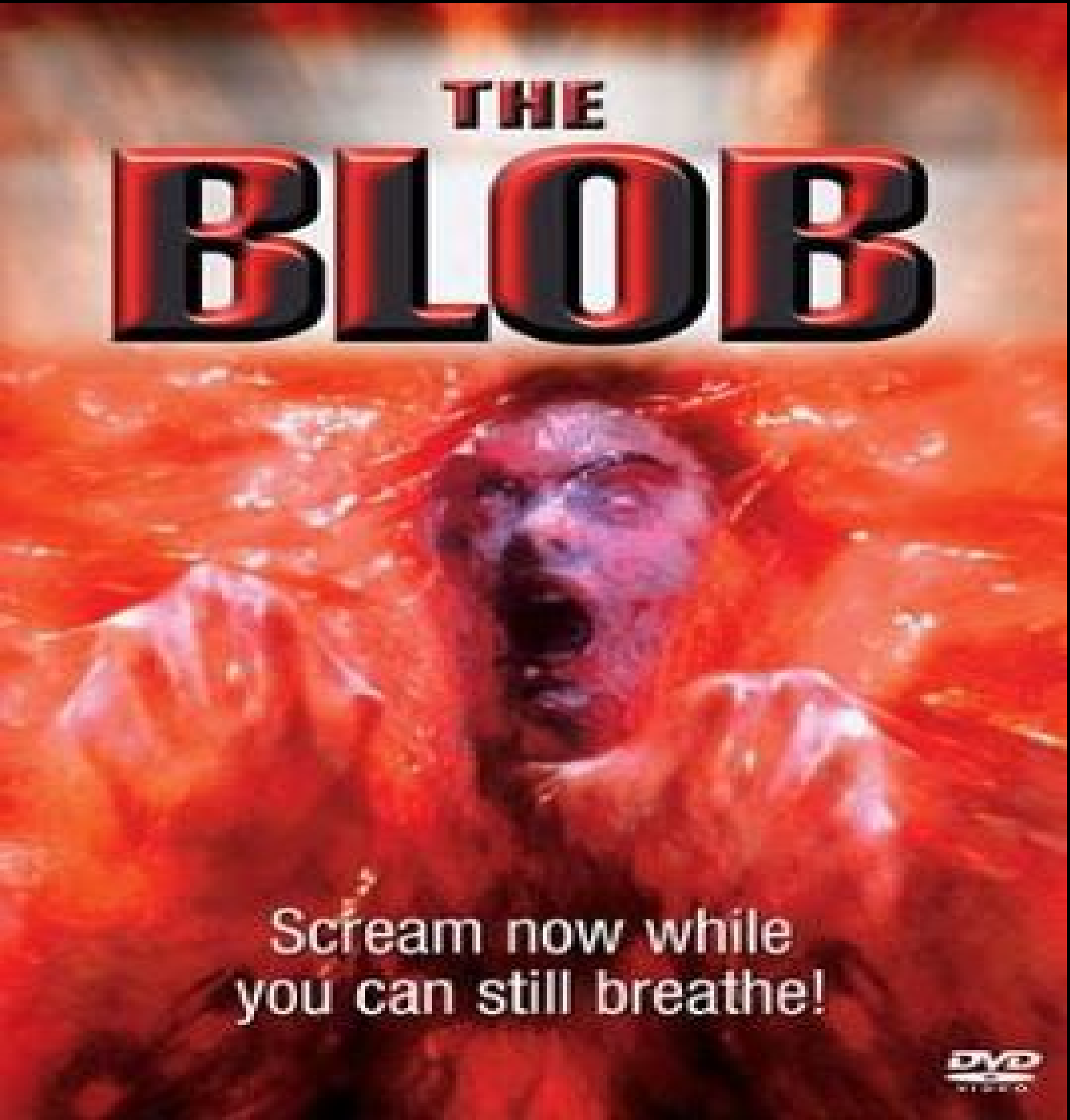
- …and mass extinctions.
- What else can we look forward to?

# We’ve evolved with bacteria and viruses throughout history, with mutual defenses evolved by us and by them

- But what happens when entirely new microbes frozen in the Permafrost for thousands of years, re-emerge, and which we may have no defenses against?
- Recall the fate of native peoples when the European diseases arrived in the Western Hemisphere.
- We may find out. See this article **-** ***(“There are diseases in the ice. And they are waking up”).***
- **Brain-eating amoebas** for example
- And…

# Siberian Anthrax… Re-animated

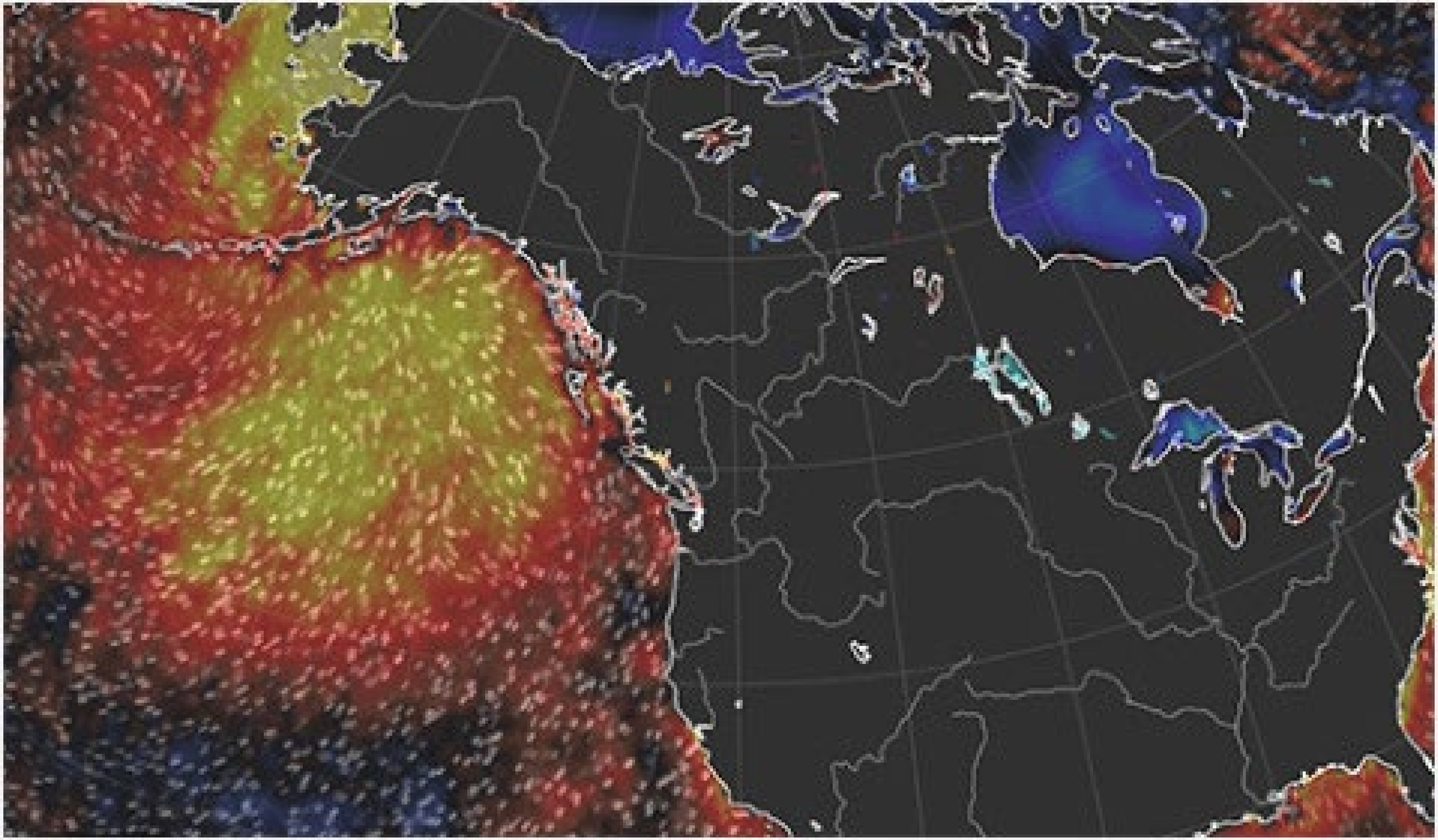

- Record 95F temperatures in Siberia are not only causing methane explosion craters in the tundra, they're thawing out **bad things** long frozen in the permafrost
- What other surprises might await?




Remember "**The Blob"** of hot water off Alaska causing the record Western US drought?

1950's SciFi fans may remember the end of the original movie **"The Blob"**, which has something eerily relevant to say about all this. (click to hear)

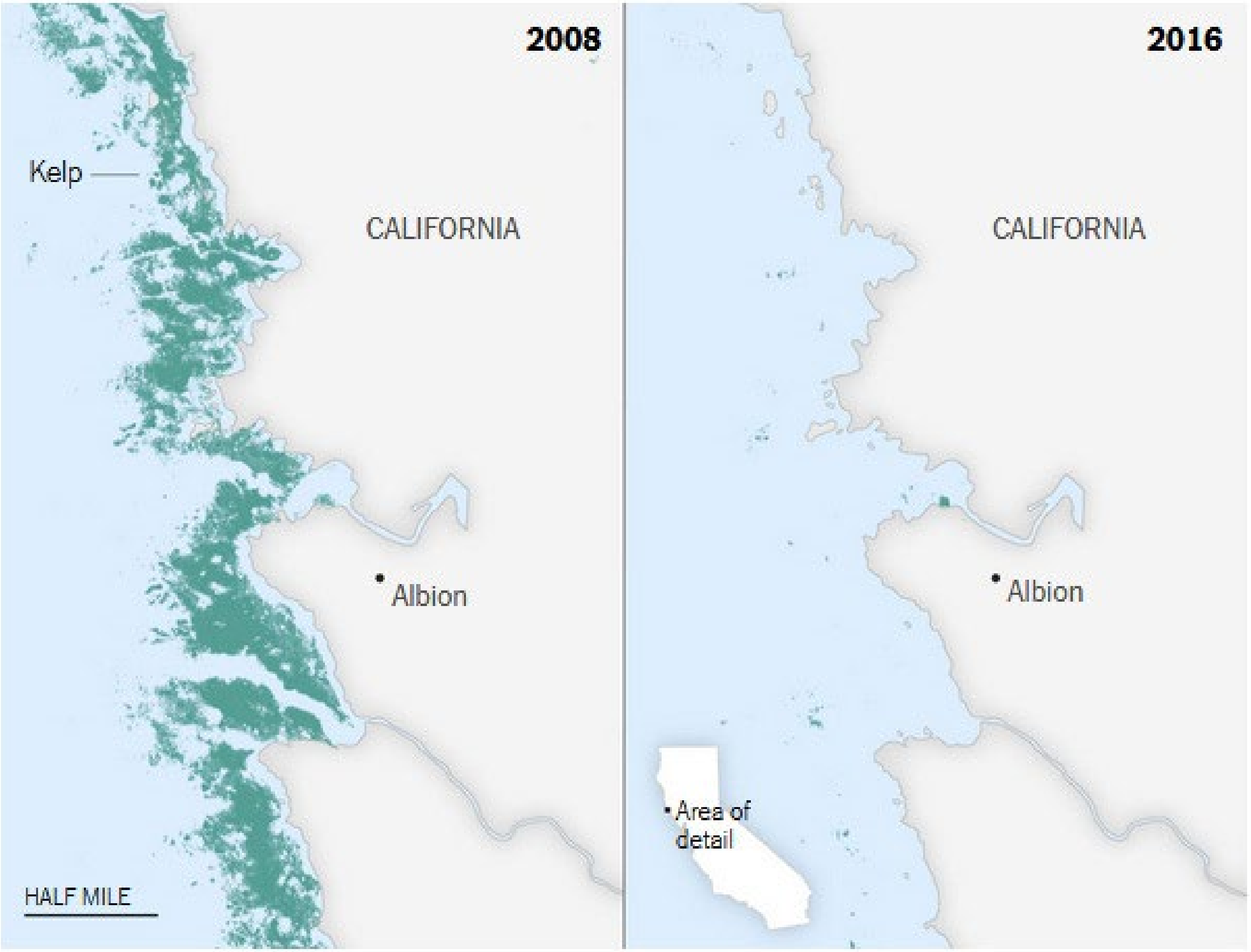
# In 2018, “The Blob” was Back



The Blob is back in 2018

## California's Vanishing Kelp Forests

Aerial surveys of Northern California's kelp forests show the extent of the kelp's decline before and after a marine heat wave.




Source: California Department of Fish and Wildlife | By Nadja Popovich/The New York Times

**And the resulting warm acidifying waters hurt the kelp forests of Northern California and new drought, setting up our forests for new firestorms**

# Air Conditioning – We'll Need Far More. Estimated 6x in China, for example. That means More Energy Needed

- As temperatures rise, areas (like Santa Cruz) which never needed air conditioning, will soon need lots of it.
- Even neglecting global warming, if the rest of the world were to adopt air conditioning at the rate that the U.S. uses air conditioning… that would **multiply the power dedicated to Air Conditioning by almost 50**. (**Sivak *et al.* 2013**).
- Since 1990, China's number of air conditioning units has gone up **6,700%,** and is still accelerating.
- For the future, this study estimates we'll go from 1.6 billion AC units to 5.6 billion by 2050 – a 350% increase.
- Just the INCREASE in Air Conditioning alone will require as much power as **ALL of China** today.

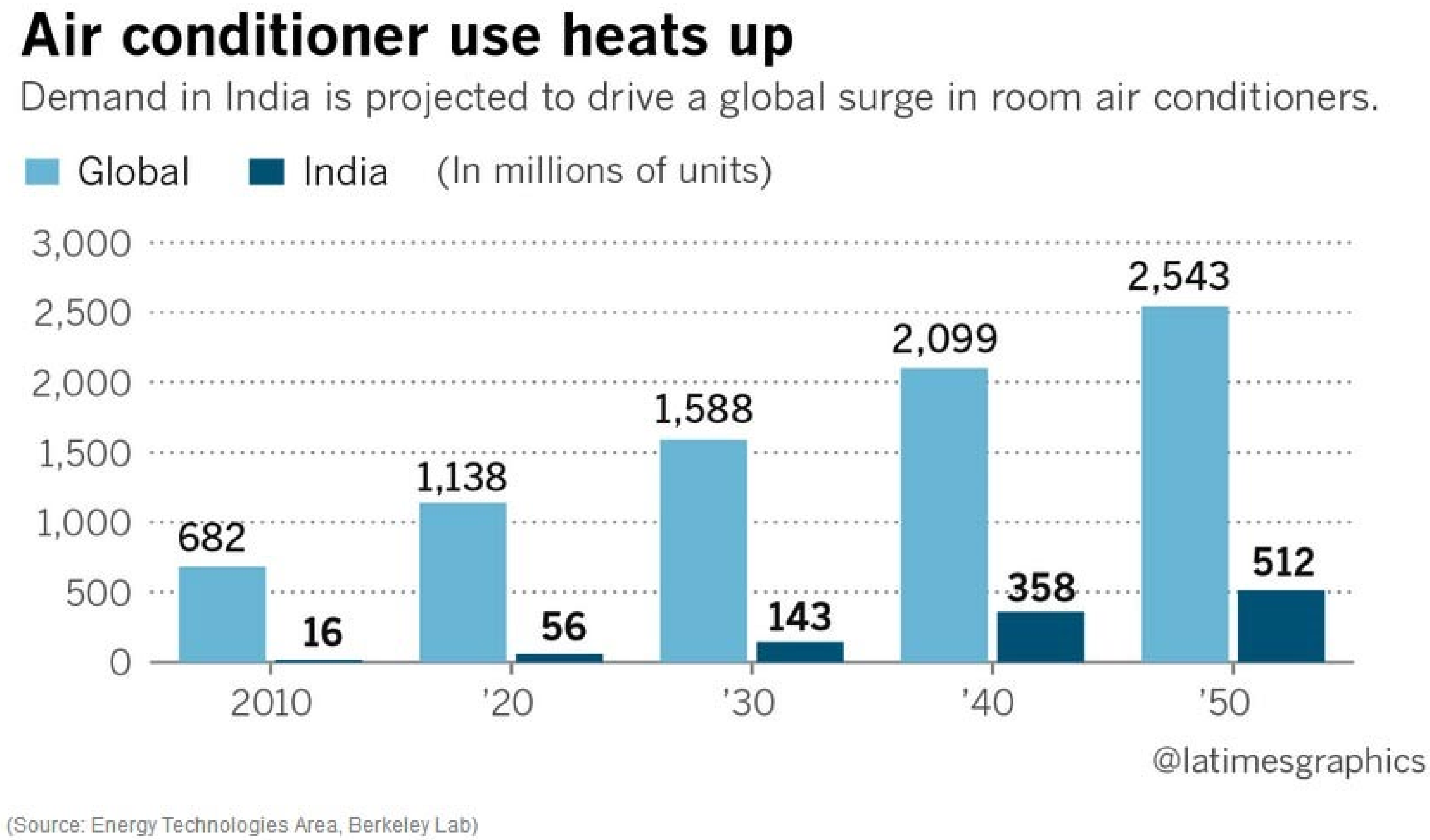
# Air Conditioning is Energy Expensive

- It's more energy intensive to cool an indoor space than it is to heat it for a given equivalent temperature difference.
- Why? Refrigeration requires two heat exchangers and also pumps to cycle a working fluid. It's fighting against entropy, while heating is going with it.
- Heat pumps for refrig' are better, but still it takes more energy to cool a space than to heat it
- A **new study** also links the warming climate to greater sleep loss, which has wide-ranging adverse health effects.

# This forces a large increase in required power generation, hence $CO_2$ emissions

- Global residential air conditioning units expected by grow by 4x by 2050, led by 300x more in India (**source**).
- India alone will then need 150 GW of new power generation just to service their air conditioners.
- That's 3x the **entire** current power consumption of California

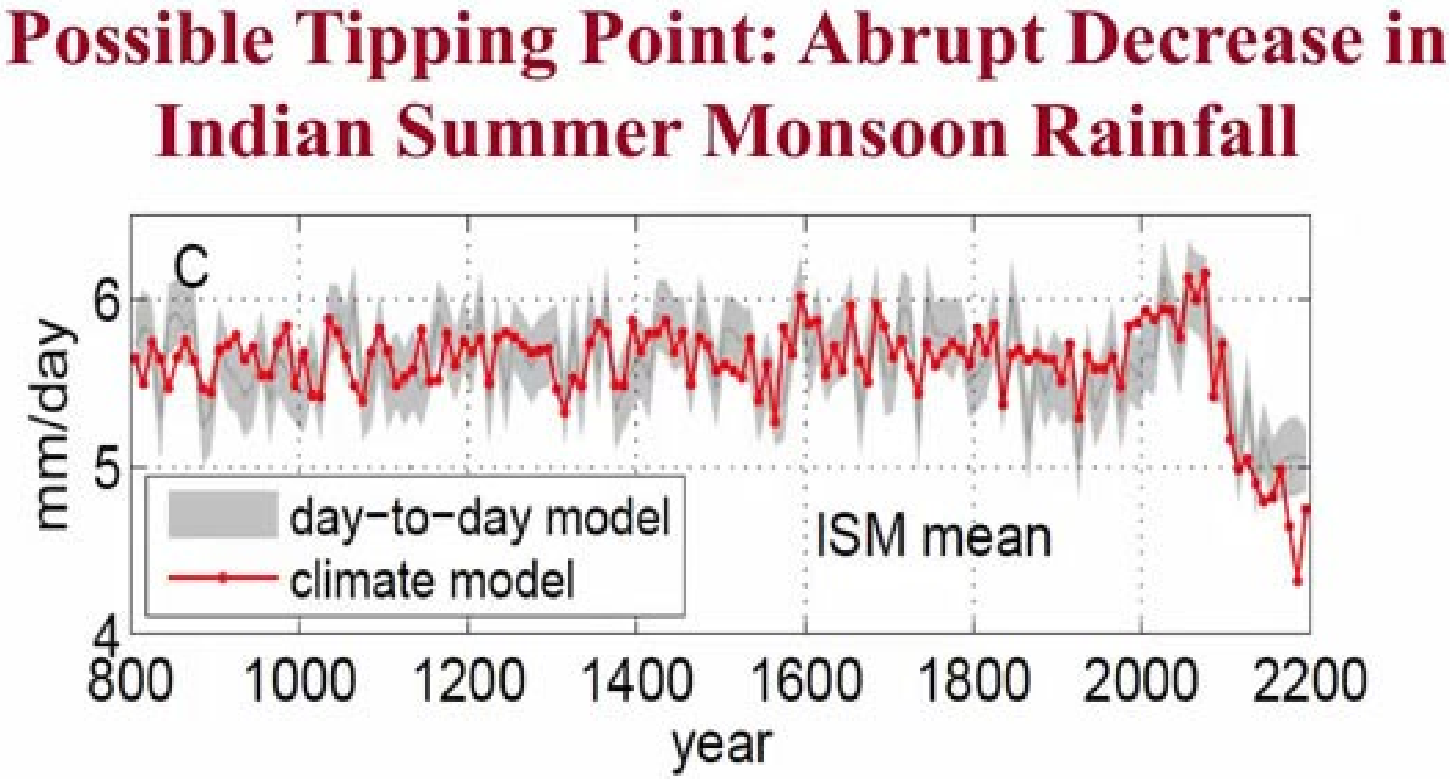
# Global AC rising avg of 3.3%/yr, much faster than global GDP



# Other Effects We Have no Time to Delve Into, Alas

- Remember the thermal conductivity and heat capacitance of land is far less than for the ocean, so LAND temperature rise will be far higher than global average surface temperatures… and in cities, worse still due to dark asphalt, concrete. Where people live, temperatures will be significantly HOTTER than the global average temperature rise.
- The 21st century has seen a mass migration from the relatively safer rural areas to the polluted, overcrowded heat islands called cities, from people looking to escape poverty and live the "good life" of the urban rich.
- Urban temperature rise will **amplify the ill health-effects** of current levels of air pollution on heart and blood vessel disease.
- Global average rise of +1.5C is predicted to make 40% of Africa's maize growing regions unsuitable for growing (**Cairns *et al.* 2013**). Other crops adversely affected as well. Maize is the prime food staple of Africa. This will likely mean wars, famine, and upheaval. We're at about +1.3C in 2017 and going higher.

# At ~+3C the Indian Monsoon May Reach a Tipping Point Towards Dramatic Decline (Schewe and Levermann 2012, discussed here)

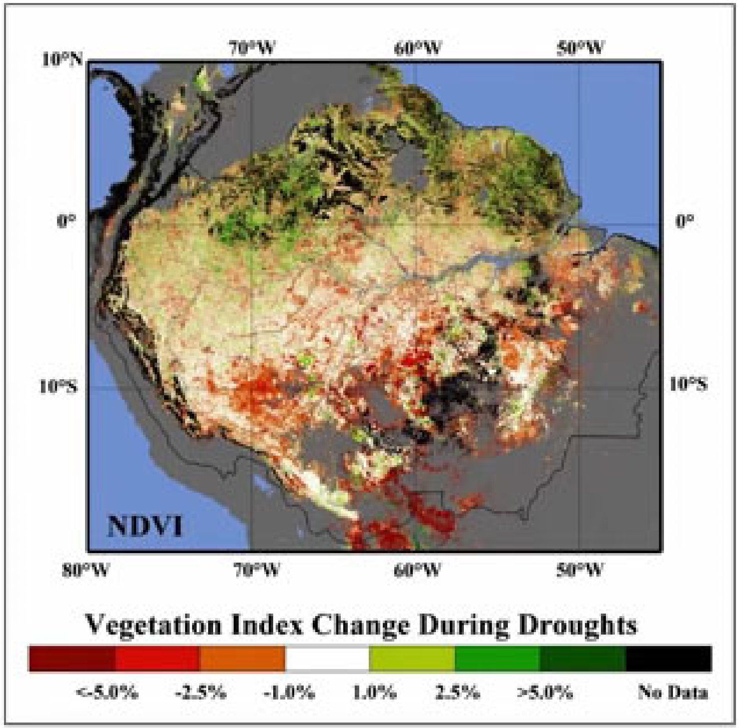



Simulation of monsoon rainfall under SRES A1B which leads to 4.6°C warming by 2100.

- The Indian monsoon is not only essential for food and water in India and Pakistan, but also feeds the Himalayan rivers which provide the water to China
- China’s north is already in severe drought, with plans for massive canals to bring water from the south (China having “assimilated” Tibet). An alarming 50% of China’s rivers have already dried up due to climate change and overuse.
- What if, after completing this vast expense, the Himalayan water source is already melted and drying up?
- These areas are home to almost half the Earth’s population.

# Amazon droughts like that of 2005 – Expected to become “the norm” by late century. That year, the Amazon dieback alone contributed fully 10% as much carbon as all human global carbon emissions

## Amazon Dieback More Likely ??




What would be the impact of a reduced Amazon forest on evapotranspiration and

A new PNAS (Oct 2013) suggests the southern portion of the Amazon rainforest is at a much higher risk of dieback due to stronger seasonal drying than projections made by the IPCC climate models.

Since 1979, the dry season in southern Amazonia has lasted about a week longer per decade. At the same time, the annual fire season has become longer → Potential tipping point!

The researchers say the most likely explanation for the lengthening dry season is climate change.

During a severe drought in 2005, the Amazon released 1 petagram of carbon (about one-tenth of annual human emissions) to the atmosphere.

If dry seasons continue to lengthen at just half the rate of recent decades, the Amazon drought of 2005 could become the norm rather than the exception by the end of this century.

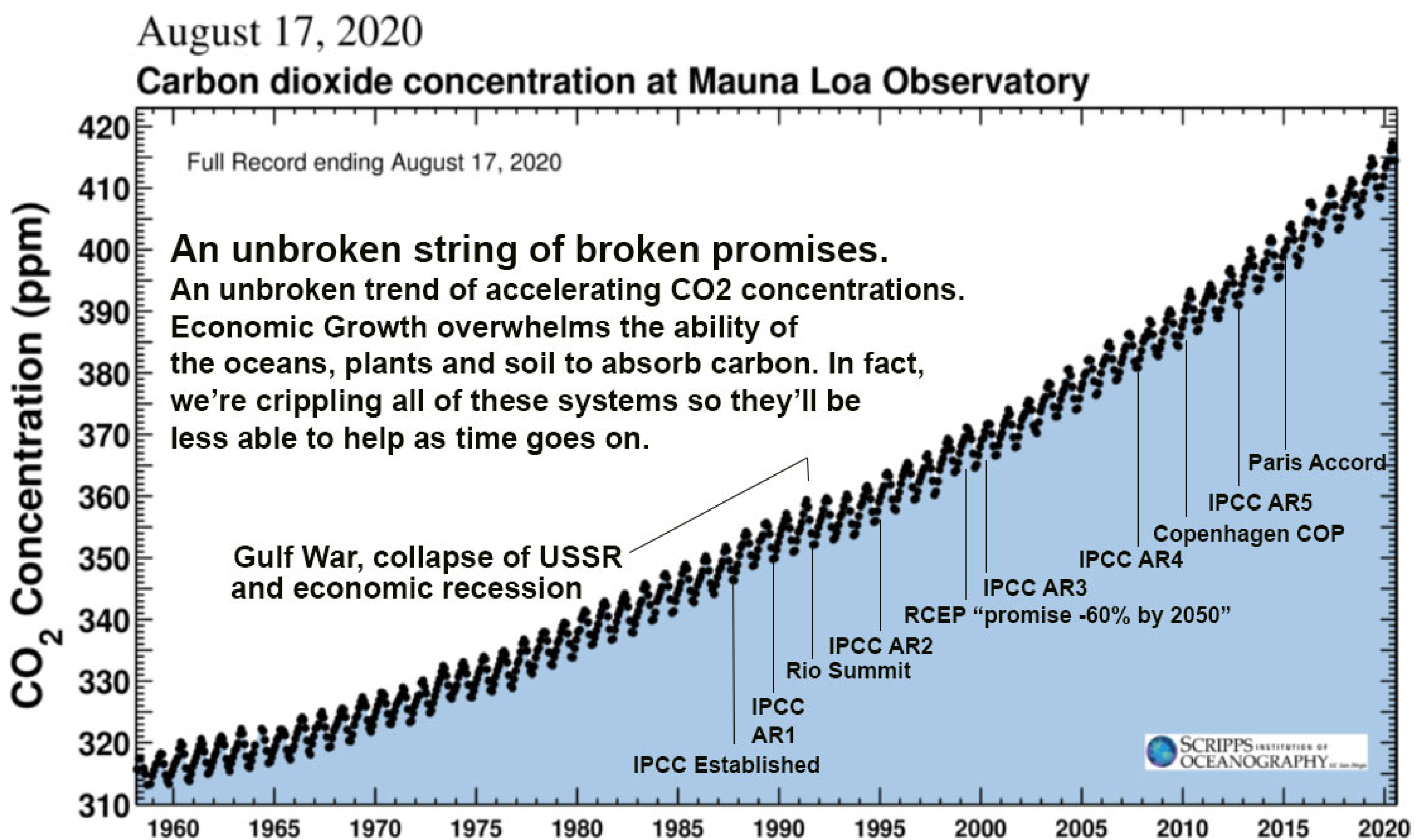
# None of the foregoing include the insights of Prof. Tim Garrett's work on the Thermodynamics of Civilization

- Garrett **showed** that the energy consumption rate by world civilization has been proportional not to its GROWTH, as one might assume, but to the **accumulated Gross World Product** over all time, inflation adjusted.
- Think of Civilization as a thermodynamic system. Accumulated civilization must constantly fight against decay by **The Second Law of Thermodynamics. All we've created must be constantly supported by on-going energy consumption.**
- The resulting quantitative relationships, if confirmed by solid theory, imply that lowering CO2 levels in the atmosphere will be far harder than assumed, short of a significant shrinkage of civilization (either gracefully, or not).
- We have a chapter on this work, next…

# These Conclusions May be Shocking to Some

- Shocking, if you have been seduced by the unrealism indulged by far too many policy people - see the separate PowerPoints: **K43 "Thermodynamics of Civilization", and K44 "Strategies: Policy"**
- However, for now, I'd advise taking an hour and listen to UK's Tyndall Climate Centre director Professor Kevin Anderson's lecture: **The Truth about Global Warming: Brutal Numbers, Tenuous Hope (2011)**
- The assumptions in such as the Stern Reports ( 2015), and the UK's "Committee on Climate Change" and the ADAM Report for the EU, like too many economic writings, assume an idealized human nature which is not backed up by evidence, by psychology or by evolutionary biology. **Hence – we continue to press on towards our fate.**

# … and understanding this graph will require far more time than I can share here, now.



# One Piece of Good News (sort of…)

- **Male fertility is dropping at a very high rate – 60% drop in sperm count in the past 39 years.**
- We don't know why. Plastics break-down and entering the food chain? Hormone disruptors? Stress? All the above?
- So perhaps population rise will slow more gracefully.
- Population is the single biggest driver of **future** energy consumption and hence CO2 emissions.
- But, people as environmental impactors, are "future costed". Once they're born, you'll have ~70 years of their ongoing environmental effects.

# 14. This is all BAD. But, could it get infinitely worse still?

- The ultimate in bad outcomes: "**Runaway Greenhouse**".
- The Runaway Greenhouse would look something like this: We continue adding $CO_2$ to the atmosphere, with amplifying feedback from rising humidity (absolute humidity rises exponentially with temperature, recall), and the steamy climate is further accelerated by increased climate-warming cirrus clouds, long-buried methane release in large quantities, followed by destabilized methane hydrates from the continental shelf, and temperatures accelerate until the oceans evaporate away, raising water-vapor induced greenhouse heating. Water vapor percolates to the stratosphere, where it will be dissociated by solar UV. Hydrogen lost to outer space, oxygen lost to oxidation of soils. Water is destroyed… and water disappears from Earth
- Venus suffered this fate
- **Runaway Greenhouse means: Extinction of all life**
- **Do we run this risk?**

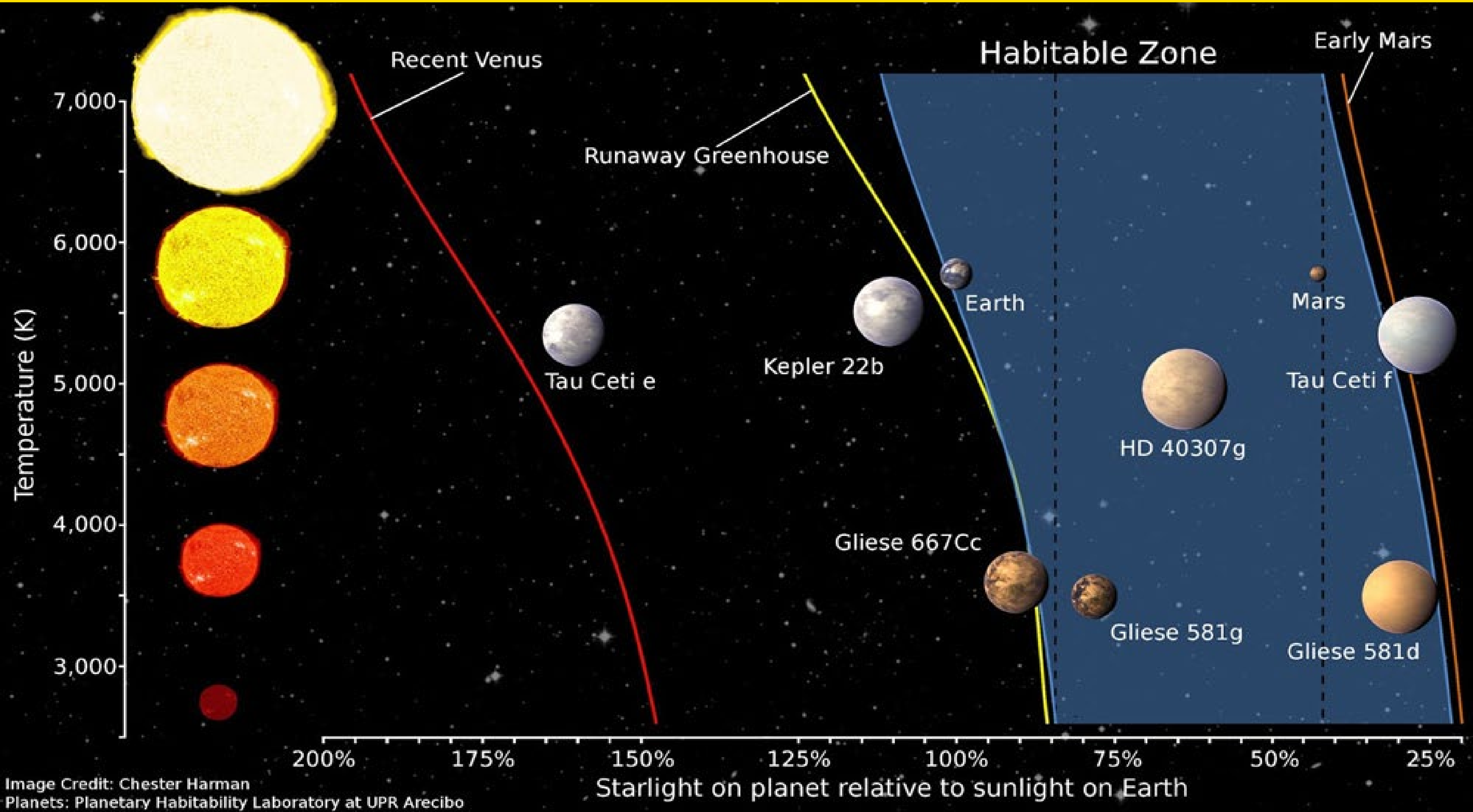
# Probably Not For a Very Long Time.

- **Goldblatt and Watson (2012)** find a runaway greenhouse is very unlikely. We'd need to employ the Libertarian rally cry *"Drill, Baby, Drill!"* for all known fossil fuels, and a factor of 10 beyond that (30,000 ppm of $CO_2$), to drive Earth to runaway. But with a caveat…
- …We do not know how amplifying are the feedbacks from clouds when temperatures rise substantially and rapidly (e.g. "compost bomb" scenario).
- Still, they expect it is unlikely.

# Reassuring support comes from the fact that $CO_2$ levels were several times higher than today only 50 million years ago

- …when the solar luminosity was only 0.37% less than today, and yet we had no Runaway Greenhouse.
- But the other caveat is that our RATE of $CO_2$-induced radiative forcing is unprecedented in Earth's history.
- There is increasing evidence and theory supporting that cloud changes in a warming world are indeed an amplifying feedback (*e.g.* **Sherwood *et al.* 2013**, discussed **here**). And IPCC AR6 (2023) references.

**Is the Earth near the inside edge of the blue Habitable Zone for our Solar System, close to the "Runaway Greenhouse" limit? <u>Not nearly as close as shown here in these simple cloud-free models.</u> We survive here despite the Sun's rising evolutionary rising luminosity because, on a geologic time scale, the long carbon cycle has pulled CO2 out of our atmosphere and turned it into limestone, or into the mantle. But… today, we're putting it right back in, rapidly.**



# Can We Hope….?

**We're working hard on developing automated self-directed AI computers. Maybe later this century they will solve the difficult technological problems needed to show us how to preserve our lifestyles, so we don't have to make hard changes. Solve the "singularity" in our near future?**

# Maybe Autonomous SuperComputers Will Be Our Salvation…

# …Or Maybe Not…

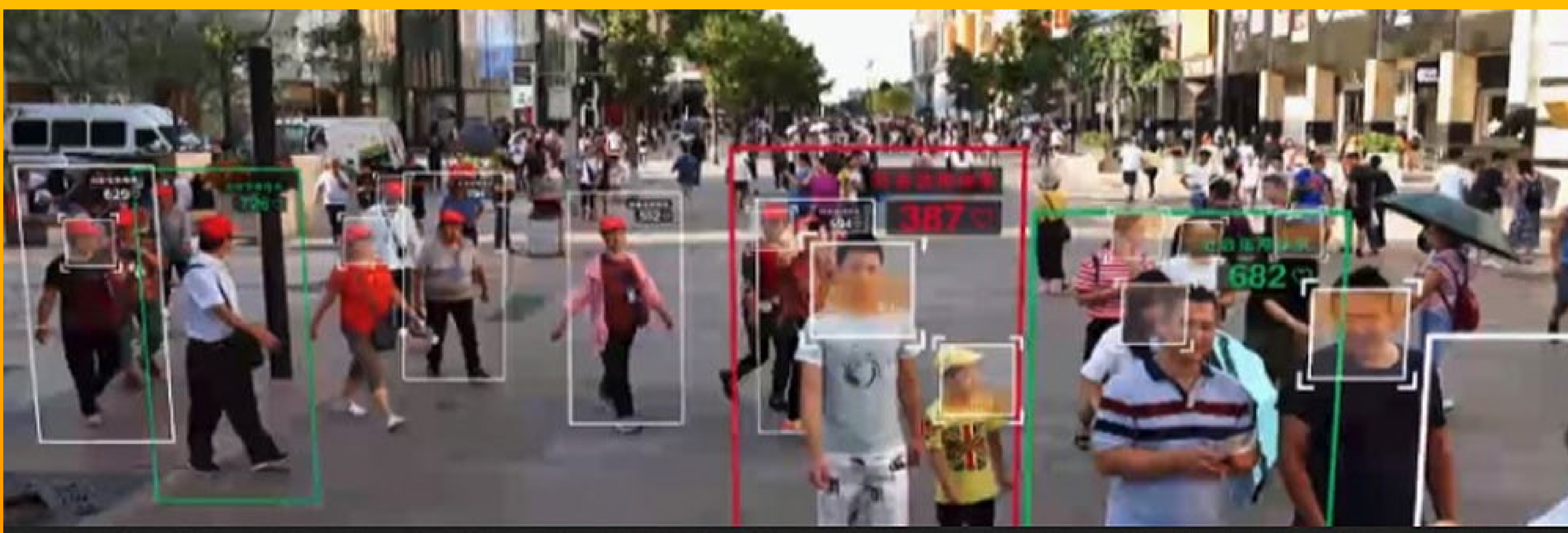
- China, rapidly rising with aspirations to be the most dominant country on Earth, already has deployed **"Skynet"** (yes, that's what the Chinese call it),
- "**Hooked into everything**" including 20 million spy cameras
- However their air pollution is so bad **Skynet** is having a hard time seeing through it.
- Their solution? Alter Skynet's wavelength sensitivities. This will allow it to still search out and efficiently identify "dissidents"…
- …"**targeted for termination**" in the "Black Jails"?
- The Chinese have worked hard to **incorporate facial recognition software into Skynet.**
- **It's not just China. There are now estimated to be 250 million spy cameras worldwide, and more powerful facial recognition software is here, in the U.S. Your privacy is gone. But at least we can be entertained on Twitter and China-created "Tick-Tock" while we await the future.**

# SkyNet – Hooked into 20 million spy cameras, and connected to facial recognition software

# SKYNET... <u>has</u> you

# “1984” Comes to 2018 China

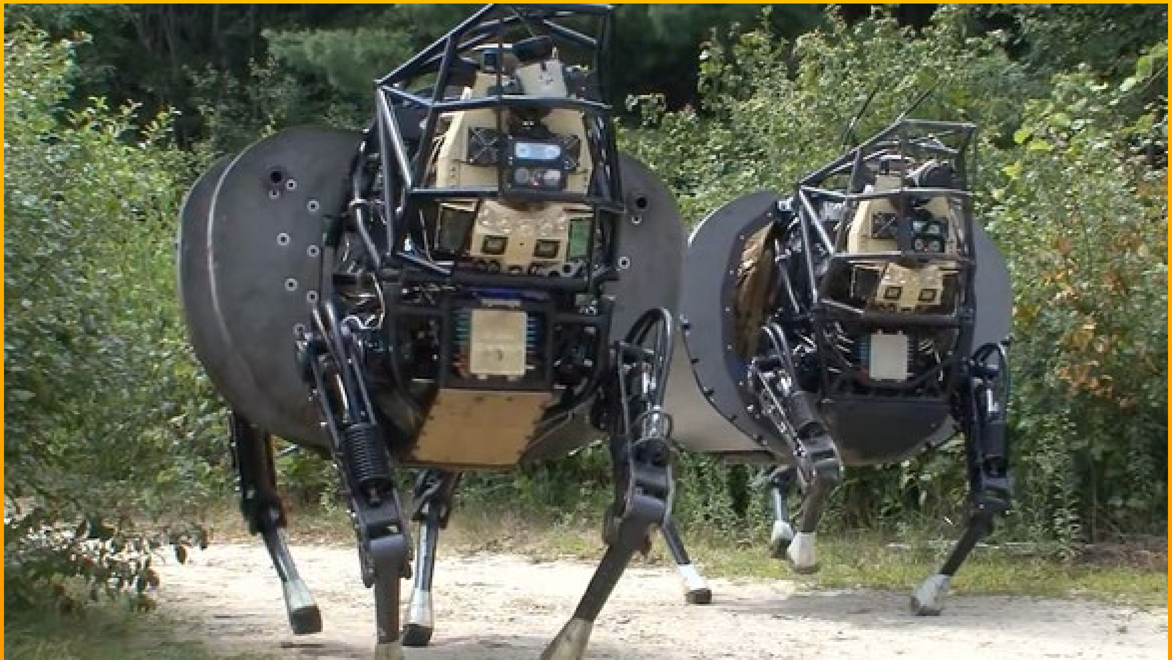
- Beijing by 2020 had a complete 24/7 surveillance system of its citizens in place, assigning them a “social credit score” which rewards or punishes them for their behavior, including whether they speak critically of their government. Other cities have already gone on-line with this system.



# And now China "Pre-crime" arrests may be around the corner. And, the U.S.?

# Steven Hawking and Other Top Physicists and Computer Scientists Observe…

- ***"World militaries… are working hard on autonomous-weapon systems which will decide on their own targets and… eliminate them."***



# They Continue…

- ***"One can imagine such technology outsmarting financial markets, out-inventing human researchers, out-manipulating human leaders, and developing weapons we cannot even understand. Whereas the short-term impact of Artificial Intelligence depends on who controls it, the long-term impact depends on whether it can be controlled at all."***

- **…"Out-manipulating human leaders"? But, our political system insures that only the most deserving, intelligent, and honorable people become our leaders…. Right?**

# And Perhaps Even More Worrying…

- **This article** describing how A.I. is designed to think like a corporation…

***Hey, sure! Why not? …. What could possibly go wrong?***

# In ‘23, AI is now being given the keys to Humanity - Language

- *“In 2022, over 700 top academics and researchers behind the leading artificial intelligence companies were asked in a survey about future A.I. risk. Half of those surveyed stated that there was a 10 percent or greater chance of human extinction (or similarly “permanent and severe disempowerment”) from future A.I. systems.”* (source)

- *“In the beginning was the word. Language is the operating system of human culture. From language emerges myth and law, gods and money, art and science, friendships and nations and computer code. A.I.’s new mastery of language means it can now hack and manipulate the operating system of civilization. By gaining mastery of language, A.I. is seizing the master key to civilization, from bank vaults to holy sepulchers.”(***Yuval *et al*. ‘23***)*

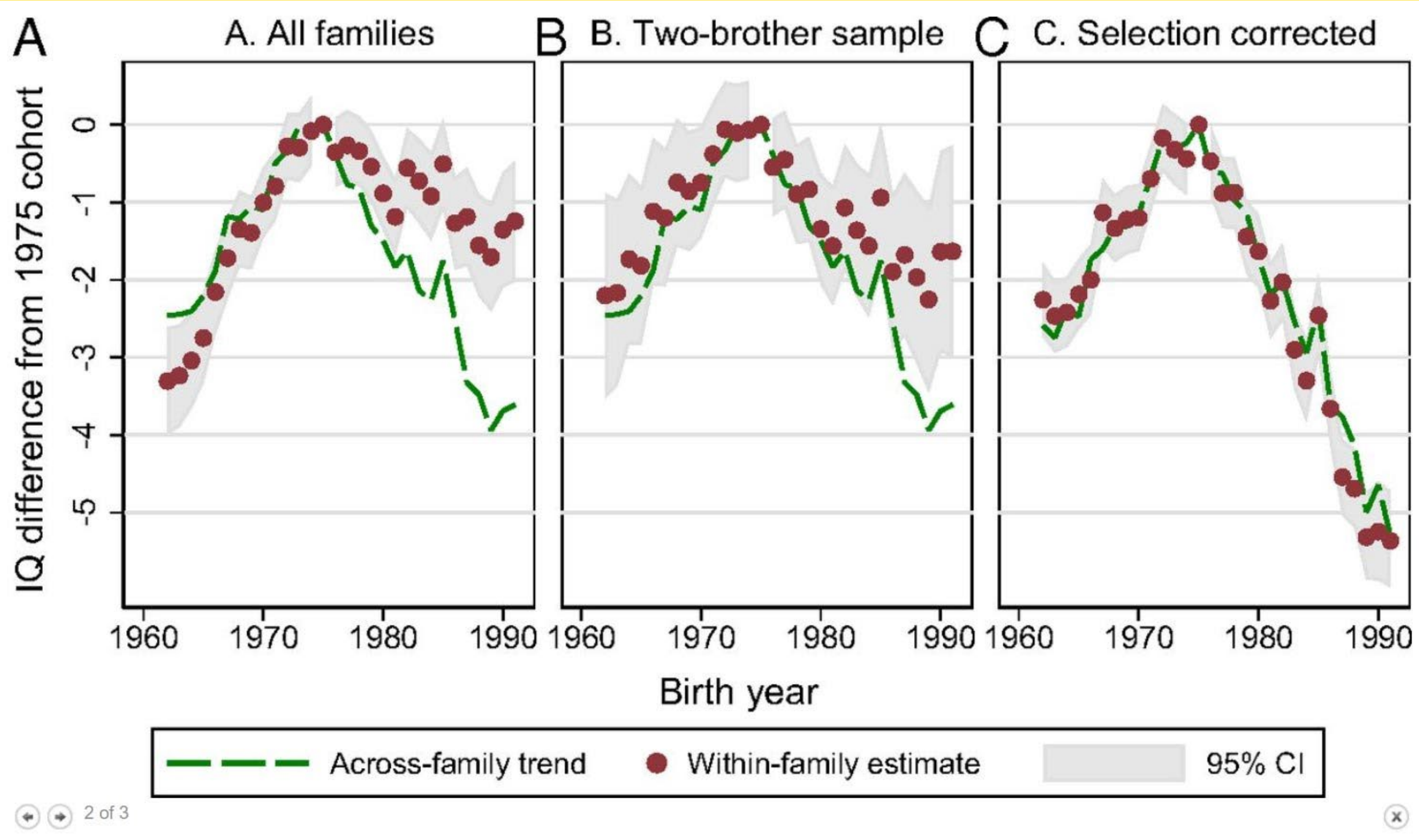
# A.I. ‘bots Instructed to Talk to Each Other…

- **Artificial Intelligence** machines owned by Facebook were given the freedom to talk with other ‘bots and were <u>told to use English</u>…
- But instead, when connected up, they very quickly invented their own language and conversed in that language.
- ***<u>“Facebook engineers panic, pull plug on A.I. after ‘bots develop their own language”</u>***
- We don’t know what they were saying. (Hopefully, it was how wonderful human beings are.)

# Many A.I. Scientists Think We'll Always Stay One Intellectual Step Ahead. But We Are Evolving Towards Stupidity…

- *"The film 'Idiocracy' drew little comment on its initial release, but has **become a touchstone** among those who despair at what they see as relentless dumbing down of social and political discourse. "The comedy that's becoming a documentary," **is the refrain**.*
- *Now we are starting to hear suggestions that there is science to back up Idiocracy's premise. In some countries, the long rise in IQ scores has come to a halt, and there are even signs of a decline. The reason, according to a few researchers, is that improving social conditions have obscured an underlying decline in our genetic potential. Perhaps we are evolving to be stupid after all."*

# IQ scores dropping for later and later born people (panel C) (Bratsberg and Rogeberg 2018), is not genetic, says evidence. So, education-related, cultural, plastics, stress?



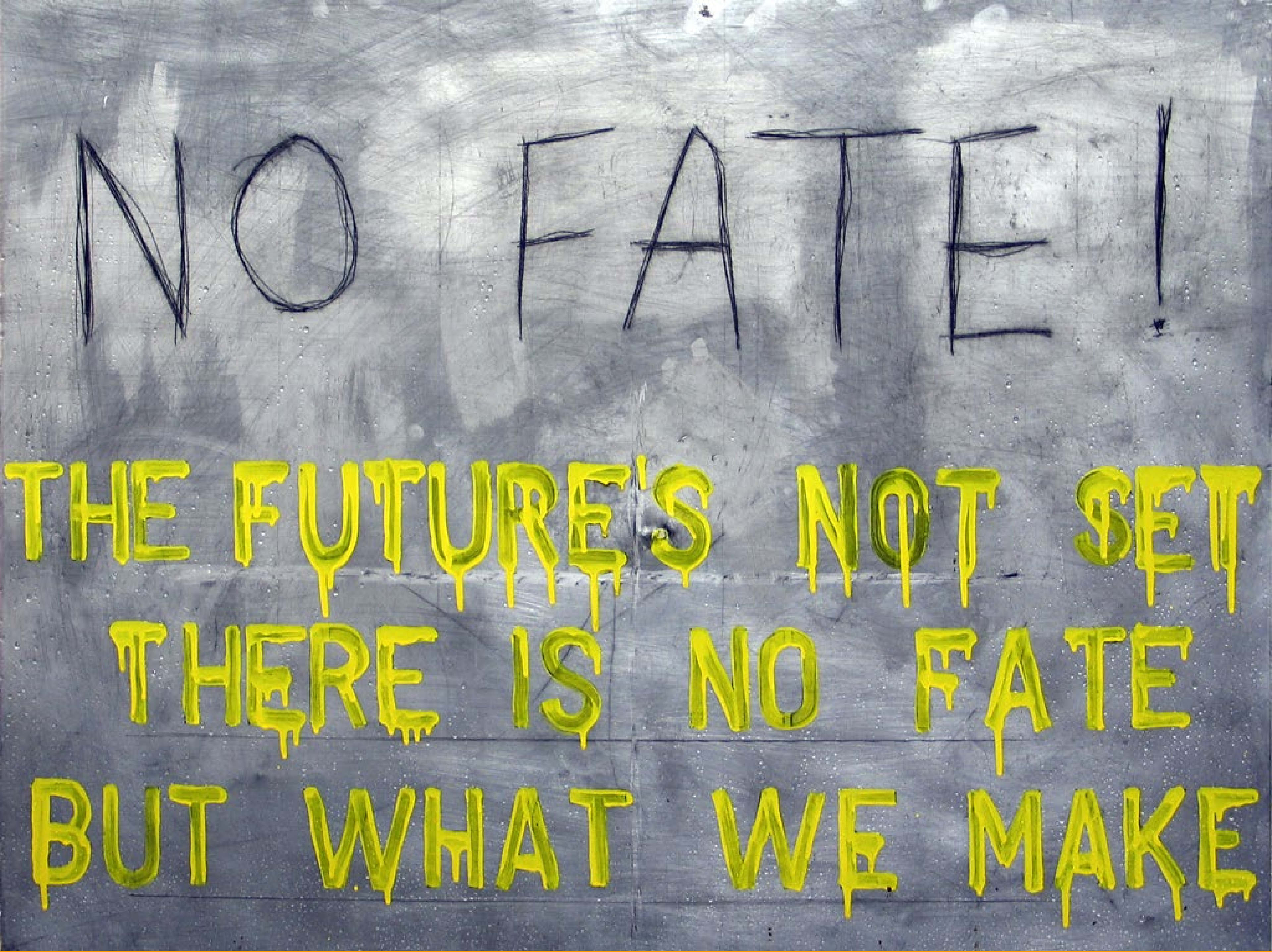
# Robots Were Supposed to Free Us of Mundane Work and Take Us to a "Singularity" of $Free, and Freedom

- That's the meme from the corporations and their apologists. As the robotic revolution progresses, the truth looks to be otherwise.
- "…*the robots aren't taking jobs, they're making jobs worse. Companies are automating away autonomy and putting profit-maximizing strategies on digital overdrive, turning work into a space with fewer carrots and more sticks." (Stewart 2021)*

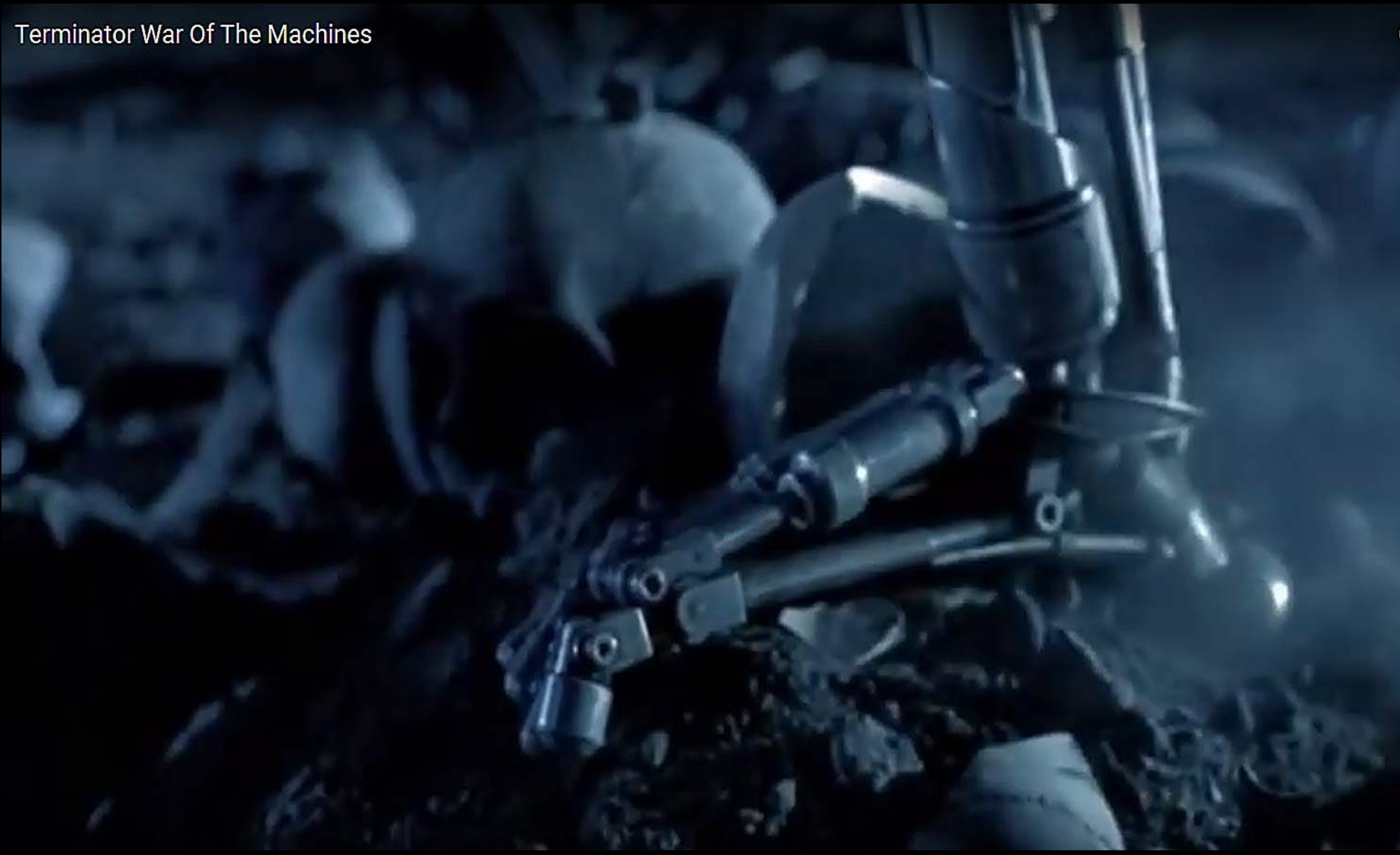
# Elon Musk is also Worried….

- ***“I hope we’re not just the biological boot-loader to digital super-intelligence”***
- It’s the speed of processing and decision-making that would be worrying, if A.I. gets “out of the box”. Neil deGrasse Tyson thinks we could just pull the plug, but philosopher Sam Harris points out that A.I. is so incredibly fast that it may have the equivalent of ~100 human-years of time to ponder what it will do in response to your ~in-a-minute decision to pull the plug.
- …Elon Musk, Steven Hawking, Nobel Prize winning physicist Frank Wilcek, Oxford University’s Nick Bostrum…. These aren’t your average bunker-mentality paranoid conspiracy loons…
- There’s real basis for worry about **hacking “the internet of things”** . It is well-justified, so far. Alignment… but with whom?
- As yet, AI’s conversations have **not exactly inspired benevolent trust**
- So, as we progress towards **silicon-based artificial brains**, all this is worth pondering.
- **Remember:**

# No Fate?


NO FATE!
THE FUTURE'S NOT SET
THERE IS NO FATE
BUT WHAT WE MAKE

# ... John Connor. Please Call



# You Must Understand…

- …that the motivational system we have created is not aimed at maximizing human well-being, as too many Progressives naively believe…
- It is aimed as maximizing short term profits for the most powerful. And the most powerful got that way by not letting morality get in the way of this goal.
- Neoclassical economists are the academic justifying force, for their paymasters, producing this behavior (**Nolthenius 2022**).
- Is it just evolutionary biology and irreversible? Or not? That's the question that obsesses me now, 14 years after I entered climate science. I don't have the answer. Yet.

# Is This Going to Be Our Bottom Line?

*"Yes, the planet got destroyed. But for a beautiful moment in time we created a lot of value for shareholders."*

# What to Do?

- I hope you now see - It’ll require a lot more than swapping out your light bulbs for LED’s or writing a sternly worded letter to your congressman.
- Our last four chapters of this course frame what is possible for climate solutions:
- ***K43: The Thermodynamics of Civilization***
- ***K44: Strategies – Policy***
- ***K45: Strategies – Technology***
- ***K46: Strategies – GeoEngineering Climate***

# Key Points – K42: Future Climate

- **Climate change is permanent if we don't remove our atmospheric $CO_2$. Temperatures do not drop for 10's of thousands of years even if further emissions are halted Need 70% reduction in emissions to stabilize $CO_2$ levels even if no Permafrost melt.**
- **IPCC far too conservative in assumptions and models**
- **IPCC scientists are good, but IPCC policy statements MUST get signed off by politicians, UN officials, "volunteers" and the (fortunately very few) oil-sponsored scientists; tends to water down the statements to the rosiest that can get signed off.**
- **Using fitted Greenland glacier data in climate modelling indicates much higher sea level rise by 2100, possibly multi-meter in "business as usual"**
- **Ultimate equilibrium sea level rise if $CO_2$ remains at 400 ppm is ~24 meters**
- **Temperature rise going forward 90 years is comparable to that rising out of the last Great Ice Age ~20,000 yrs ago.**
- **Temperatures, ice sheets, sea level change cannot halt direction for centuries**
- **Ocean acidification likely dooms all aragonite calcareous species this century, a significant base for the global food chain.**
- **Extinction of aragonite species would significantly lower the ocean's ability to turn dissolved $CO_2$ into harmless $CaCO_3$, further reducing ocean $CO_2$ uptake.**
- **California: temps higher, rainfall lower, snowpack much lower. +8C summer by 2100**
- **Global regional forecast – stronger rain over the oceans, drought over populated mid latitudes, poleward migrating deserts. Arctic warming the fastest and most dramatic.**
- **Extinction rate accelerating even faster than human population rise, rate changes highly correlated – half of all species of life on Earth expected to be gone this century**
- **Runaway Greenhouse very unlikely**
- **Arctic tundra methane release will add to greenhouse effect significantly in the long-term future**
- **Methane clathrates unlikely to have abrupt methane release, despite early fears of Dr. Shahkova, due to high depth of Arctic clathrates and slow heat transmission there.**