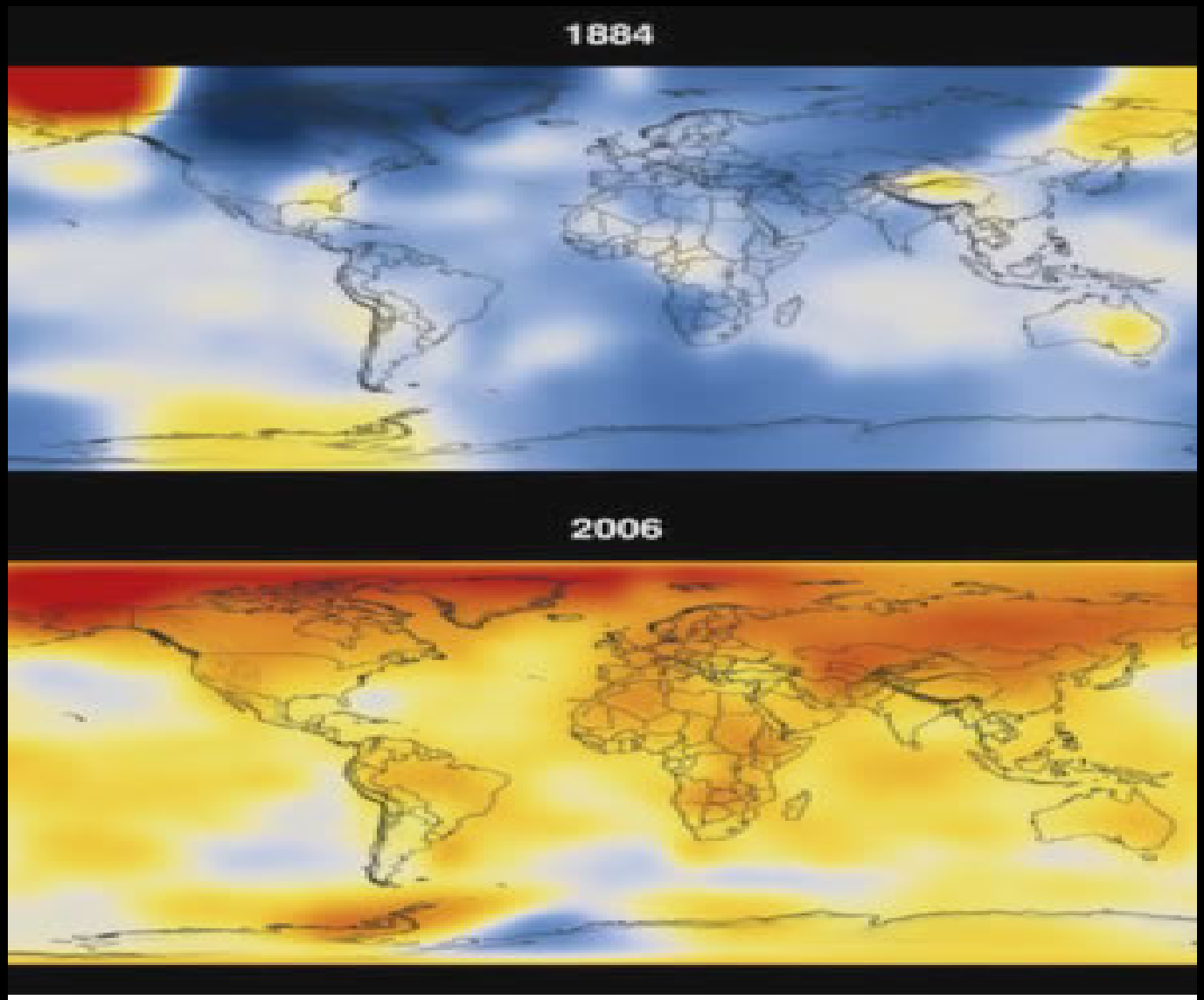
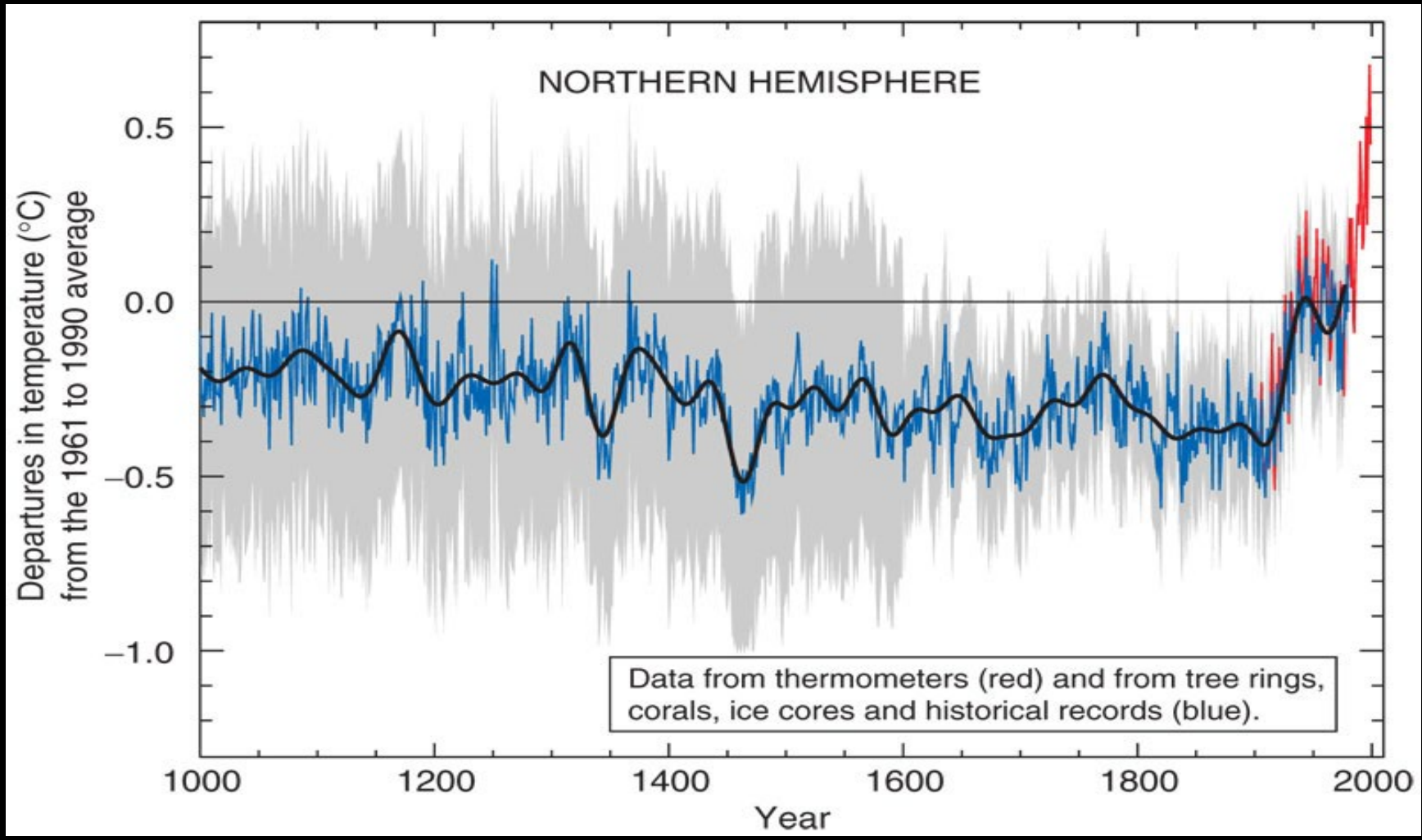
Recent Climate Change: A. Global Temperatures



Let's Put Recent Global Warming in Context of the Last 1,000 Years, up to year 2000

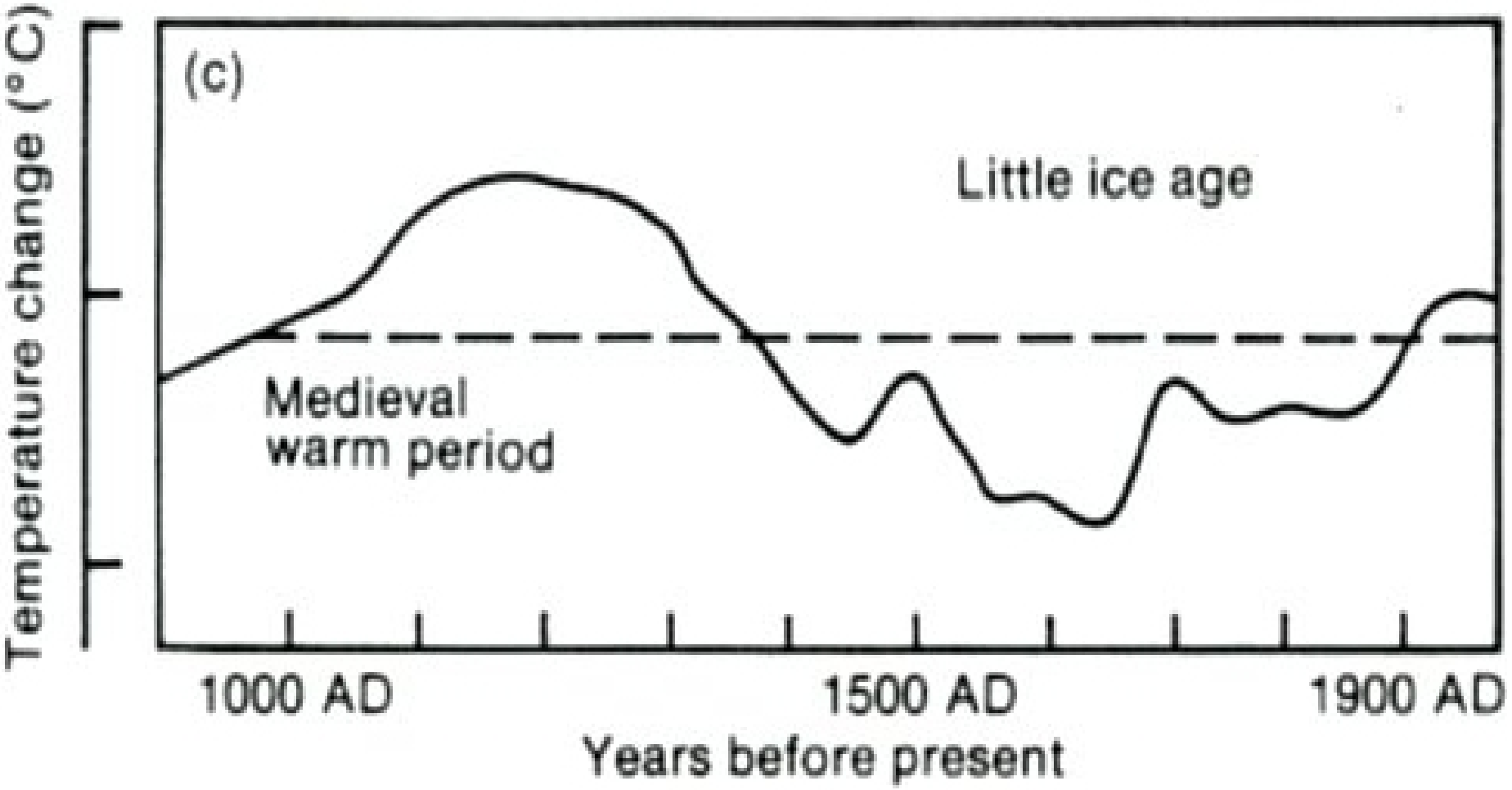


From Mann *et al.* 1999. The "Hockey Stick" made famous in "An Inconvenient Truth"

This Slide Ignited a Firestorm from the Climate Denialists

- While the best temperature data for centuries past has been updated since this 20 year old graph, It remains a simple, visually stunning image of current temperature's rapid rise, unlike anything "natural" in human history.
- Featured in the much-hated (by conservatives and other climate denialists) Al Gore film **"An Inconvenient Truth"**
- It removed one denialist claim – that the **Medieval Warm Period** was hotter than today. In fact, the MWP was pretty much missing altogether.
- How are temperatures determined here? ….

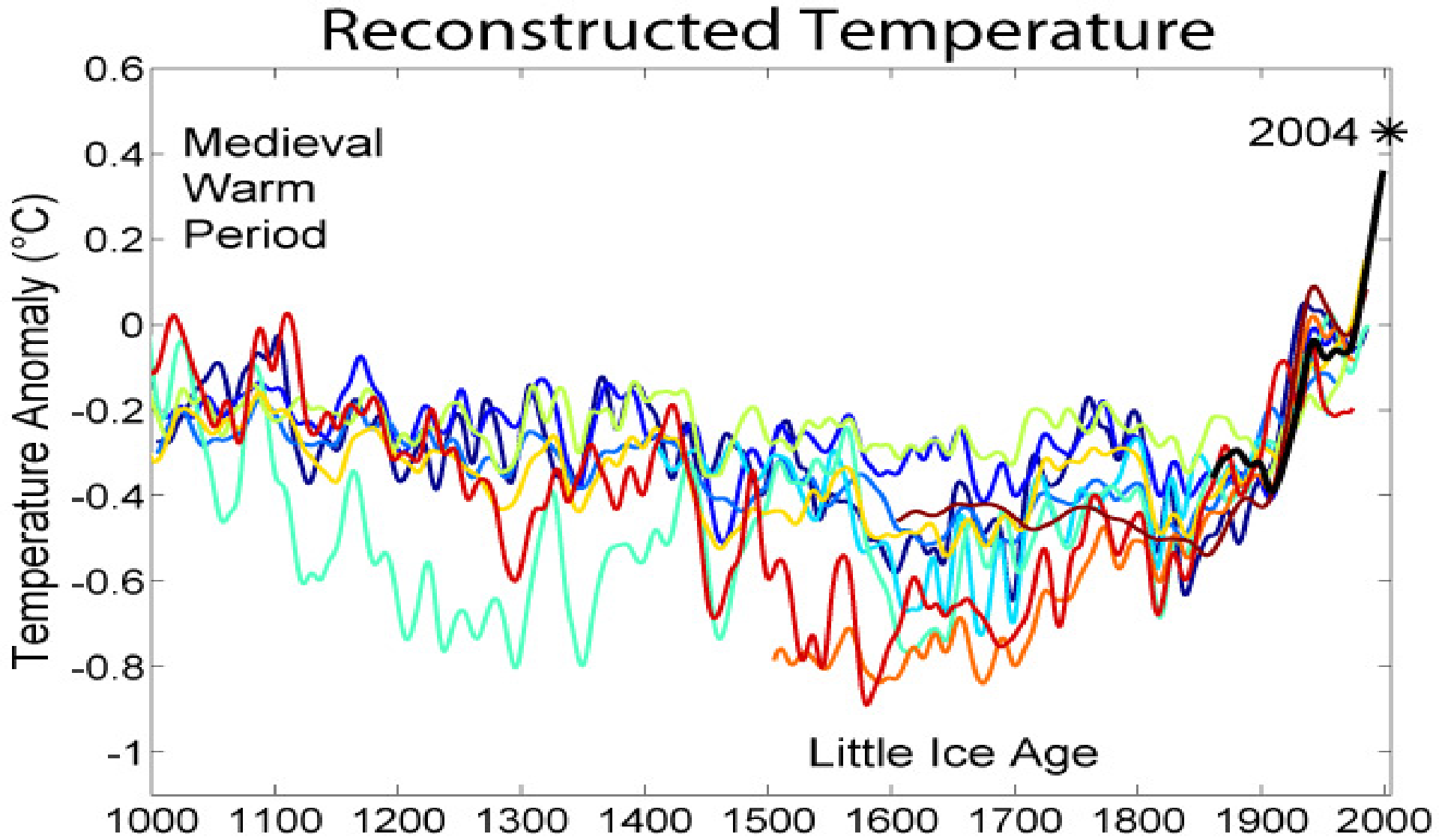
IPCC AR1 1990 Graph. Sparse Temp Data Only Available from European Records, mostly Britain. Modern Data Only Plotted till ~1979, when cool phase of PDO and aerosols still inhibited greenhouse warming. The MWP was mostly a European Phenomenon, much less when globally averaged



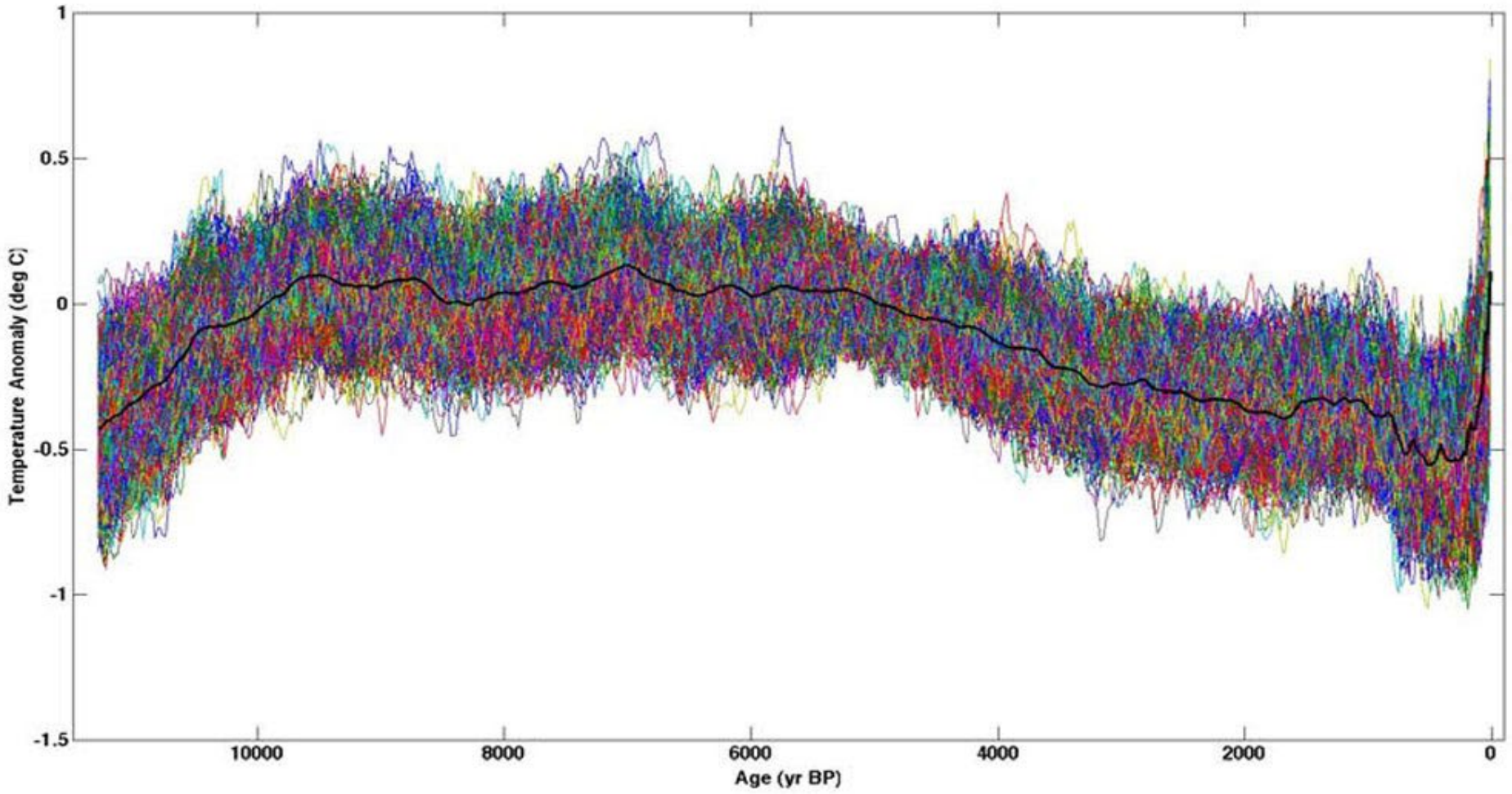
Temperature Proxies for Century, Millenium Time Scales

- (See Mann *et al.* 2008 and here, for more details), but briefly…
- **Foraminifora**: growth sensitive to temperature; different for different species. Preserved in sediments
- **Tree rings**; show good correlation to other proxies, until ~1960, when Arctic trees began to diverge from the correlation, perhaps due to unprecedented CO2 levels now far above typical values of past 1000 years
- **Stalagmites:** O18/O16 preserved in the layers gives temperature, age recorded in uranium/thorium ratio.
- **Ice cores:** trapped air bubbles preserve atmosphere, and isotope ratios are sensitive to temperature. Also trap pollen, species sensitive to temperature
- **Pollen**: the mix of plant species is sensitive to Temp. Composition in sediments from lakes, layering showing annual runoff, charcoal shows major fires which can be cross-correlated with other data
- **Borehole temperatures**: surface temperatures conduct downward through the ground, and deep measurements contain information on ancient temperatures. See NOAA's site on **borehole science**
- **O18/O16 ratios:** Oxygen18 heavier, differential chemistry at different temperatures.

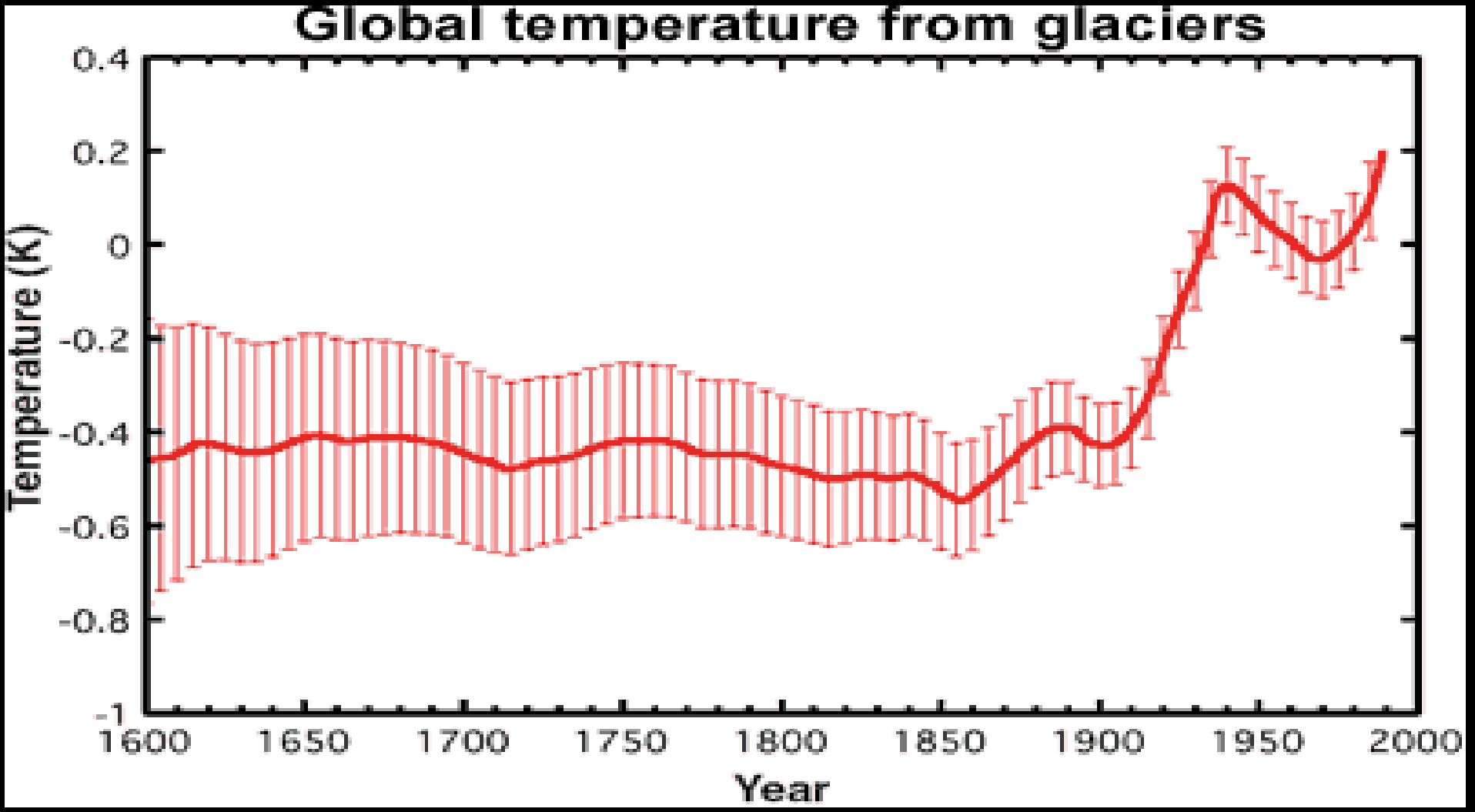
Given the importance, the work was re-done with a wider range of temperature proxies (colored) and additional care to avoid statistical over-fitting. Black=observed temps.
Result - Still a Hockey stick.



Let's go 10 times further back; Back to emergence from the last Great Ice Age… And Include more proxy data, now back 12,000 Years. Result: Still A Hockey Stick (a whole Hockey Team, as one climatalogist said)

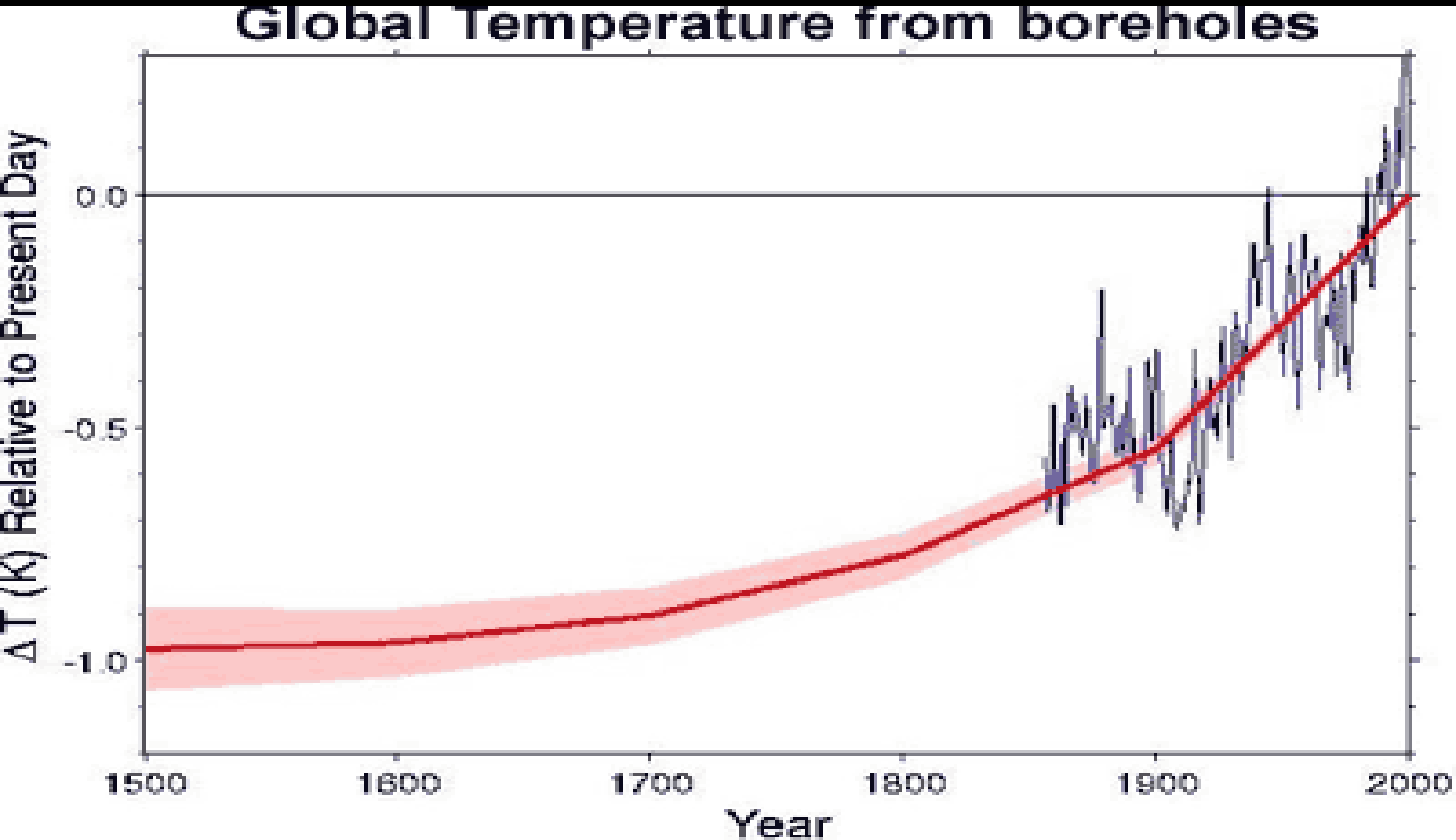


Glacier length as Temperature Proxy, calibrated from recent Temps and glaciers (Old photos, and written accounts over past 400 yrs.) Still a hockey stick

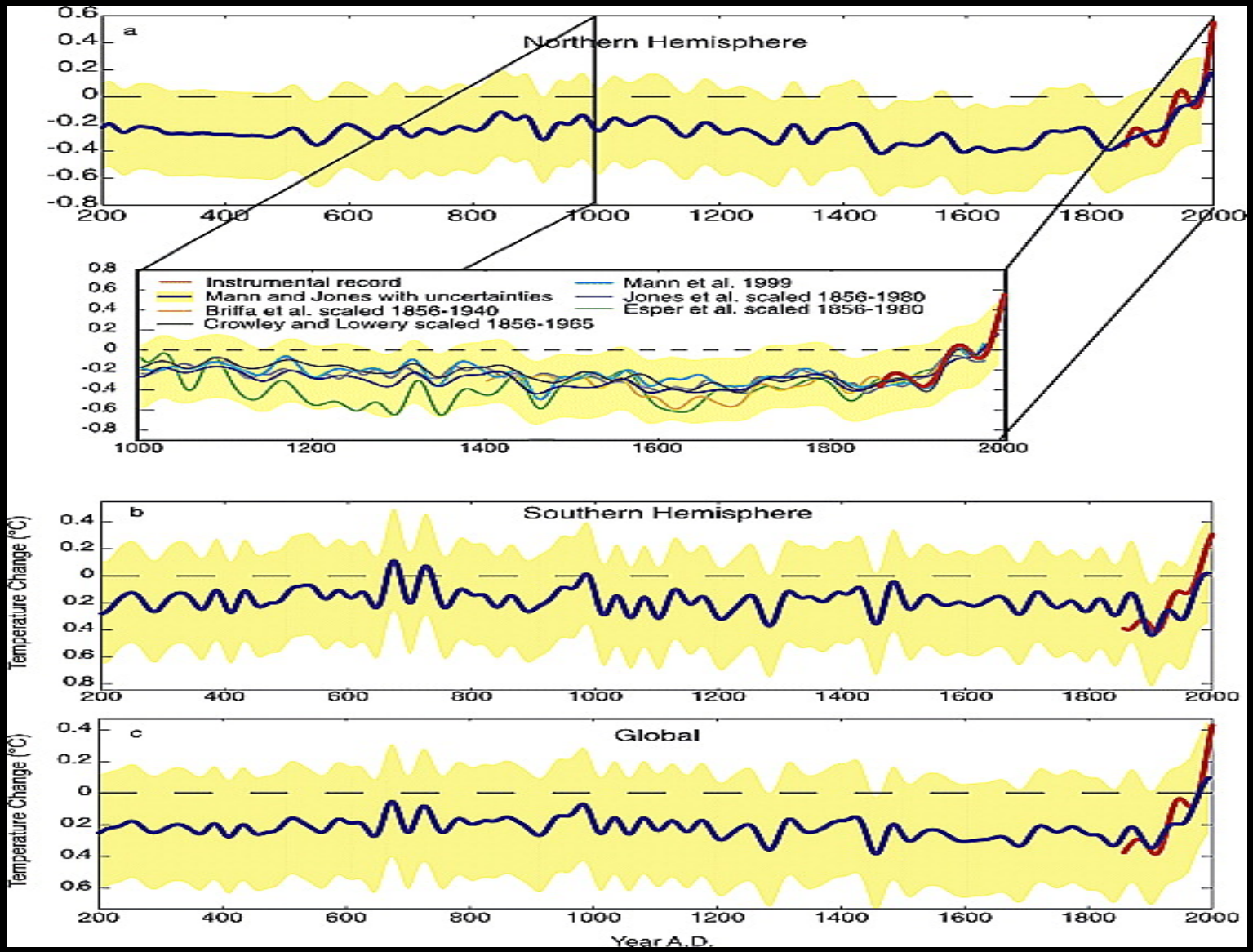


Global surface temperature change over the last five centuries from boreholes (thick red line). Shading represents uncertainty. Blue line is a five year running average of HadCRUT global surface air temperature (Huang 2000). Result:

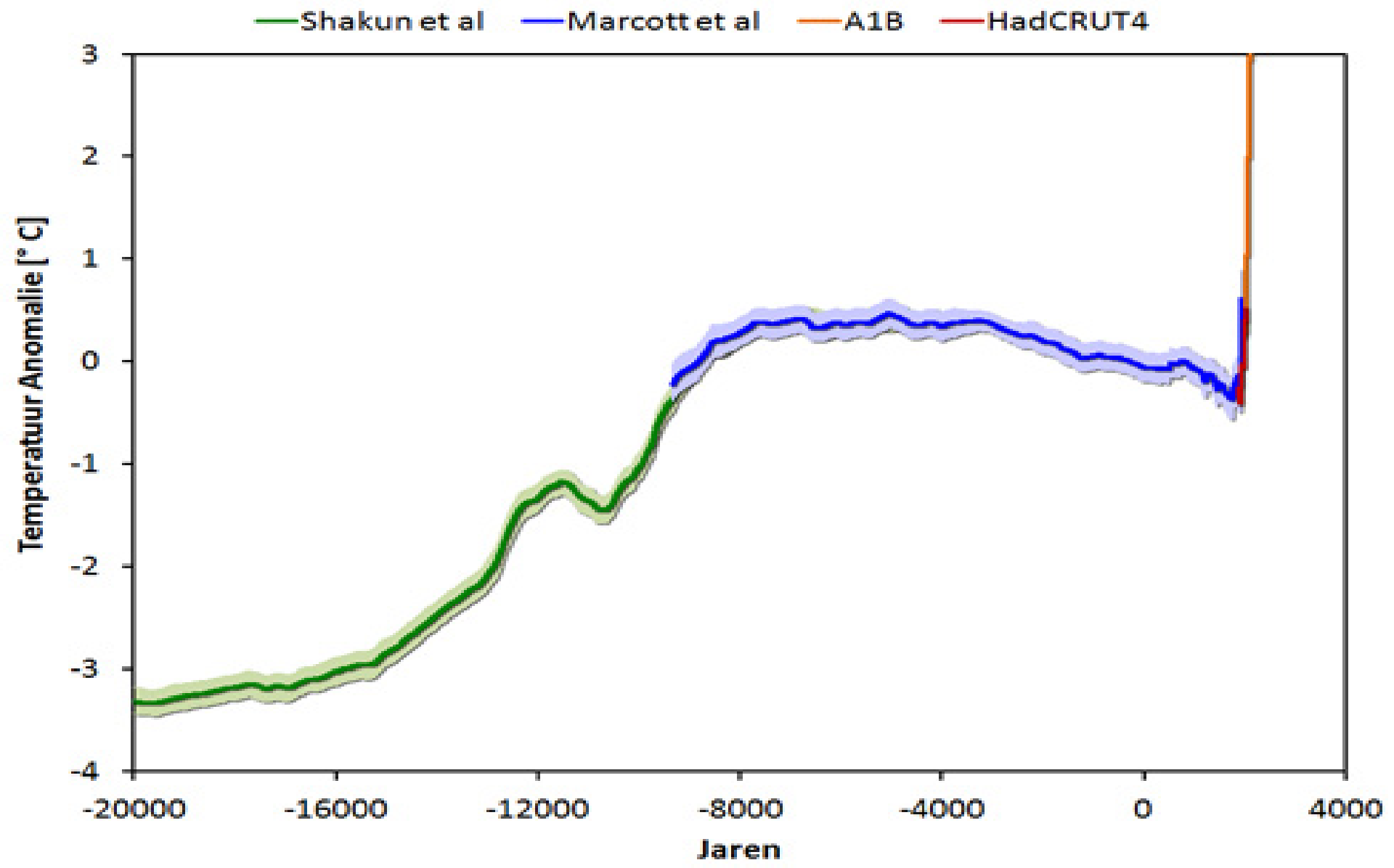
Borehole data confirms the other temperature proxies. **Still a hockey stick**



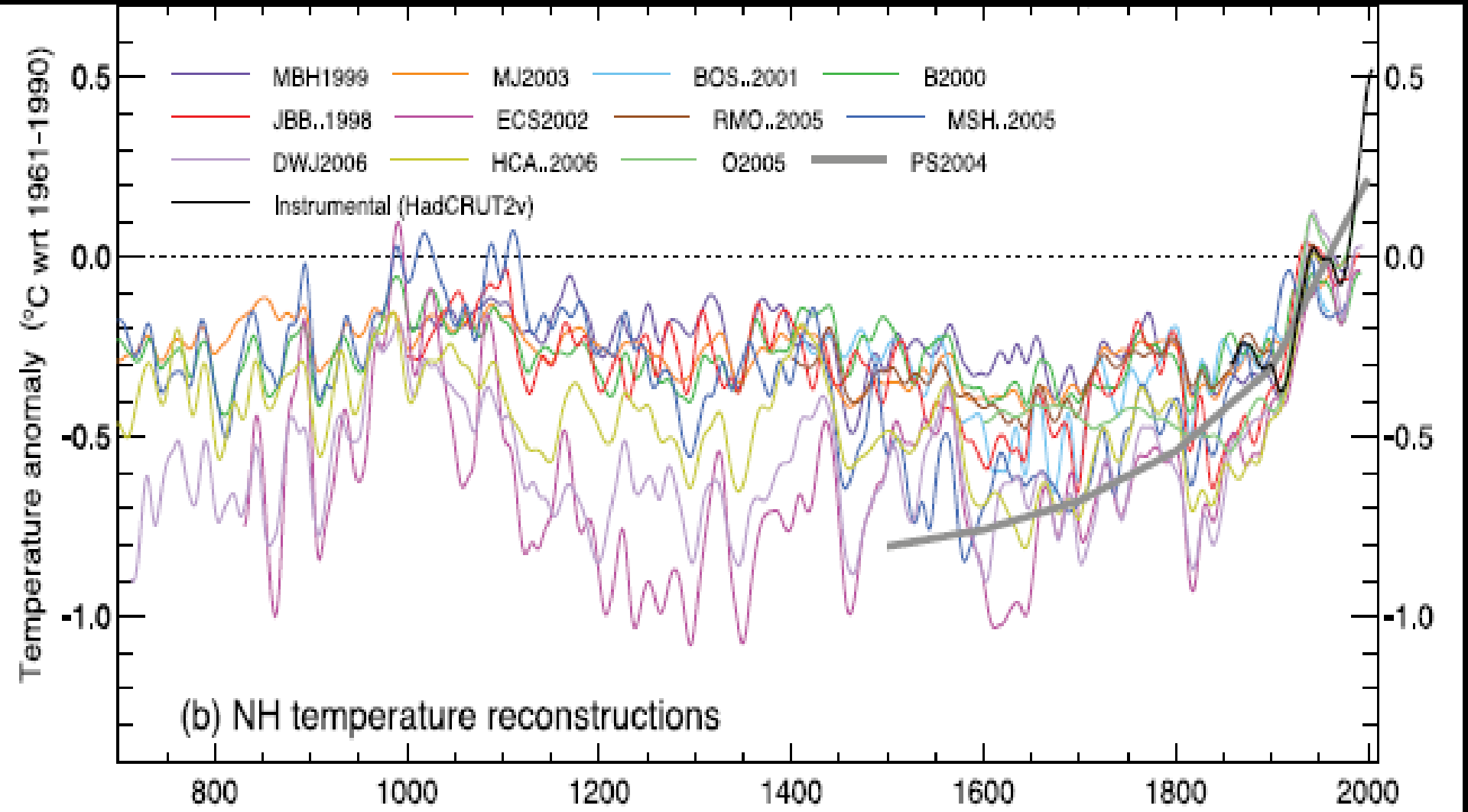
Jones and Mann (2004) temperature reconstructions using proxies, now going back 2000 years for both hemispheres, global at bottom. Instrumental temps in red instruments. Both agree - Still a Hockey Stick



10x Farther: 20,000 years now. Global temperatures since the depths of the last Ice Age; Observed (blue), current and predicted (red)



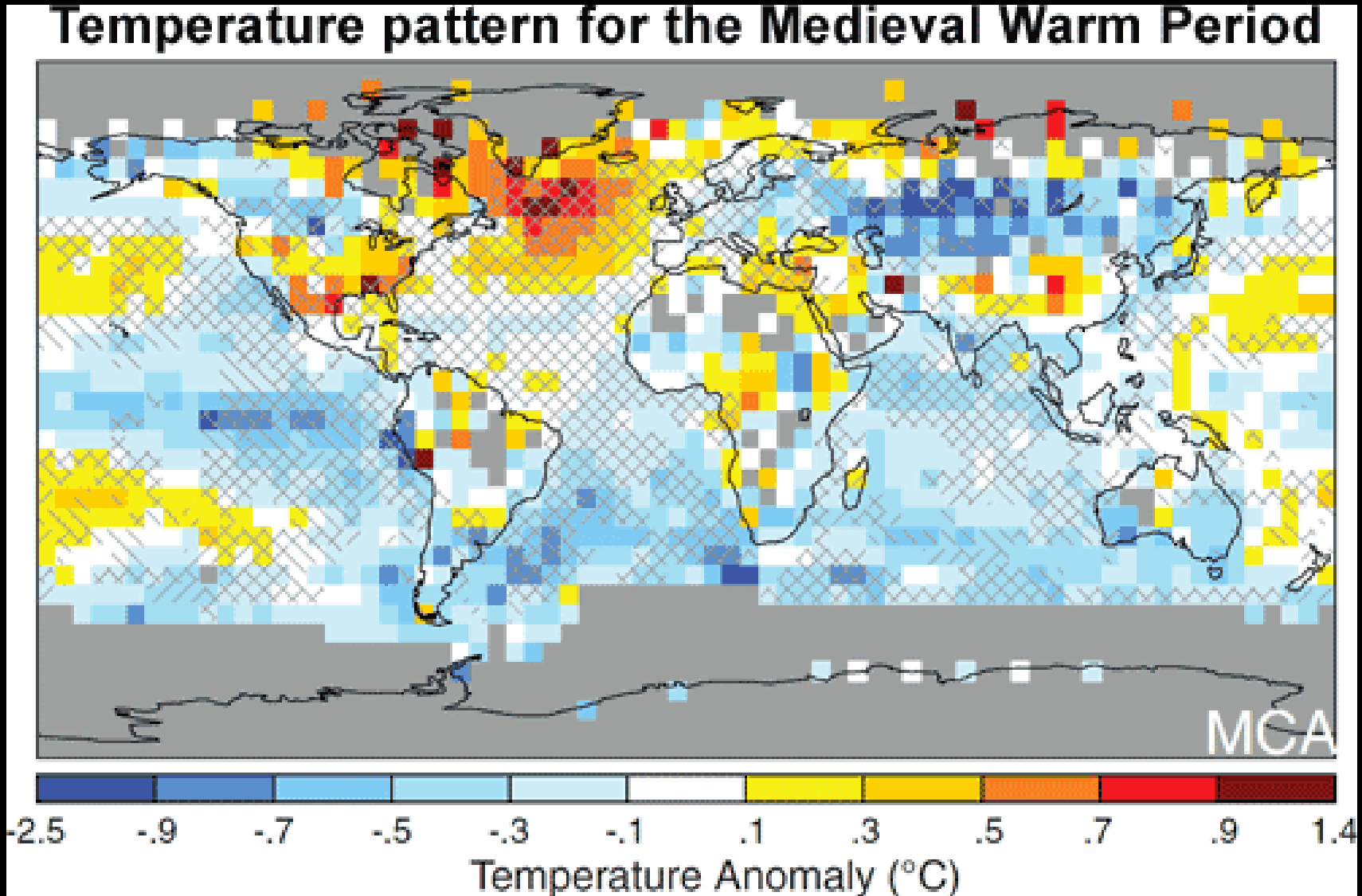
12 Different Studies of Northern Hemisphere (NH) Only. A Small Medieval Warm Period is there…in the Northern Hemisphere only



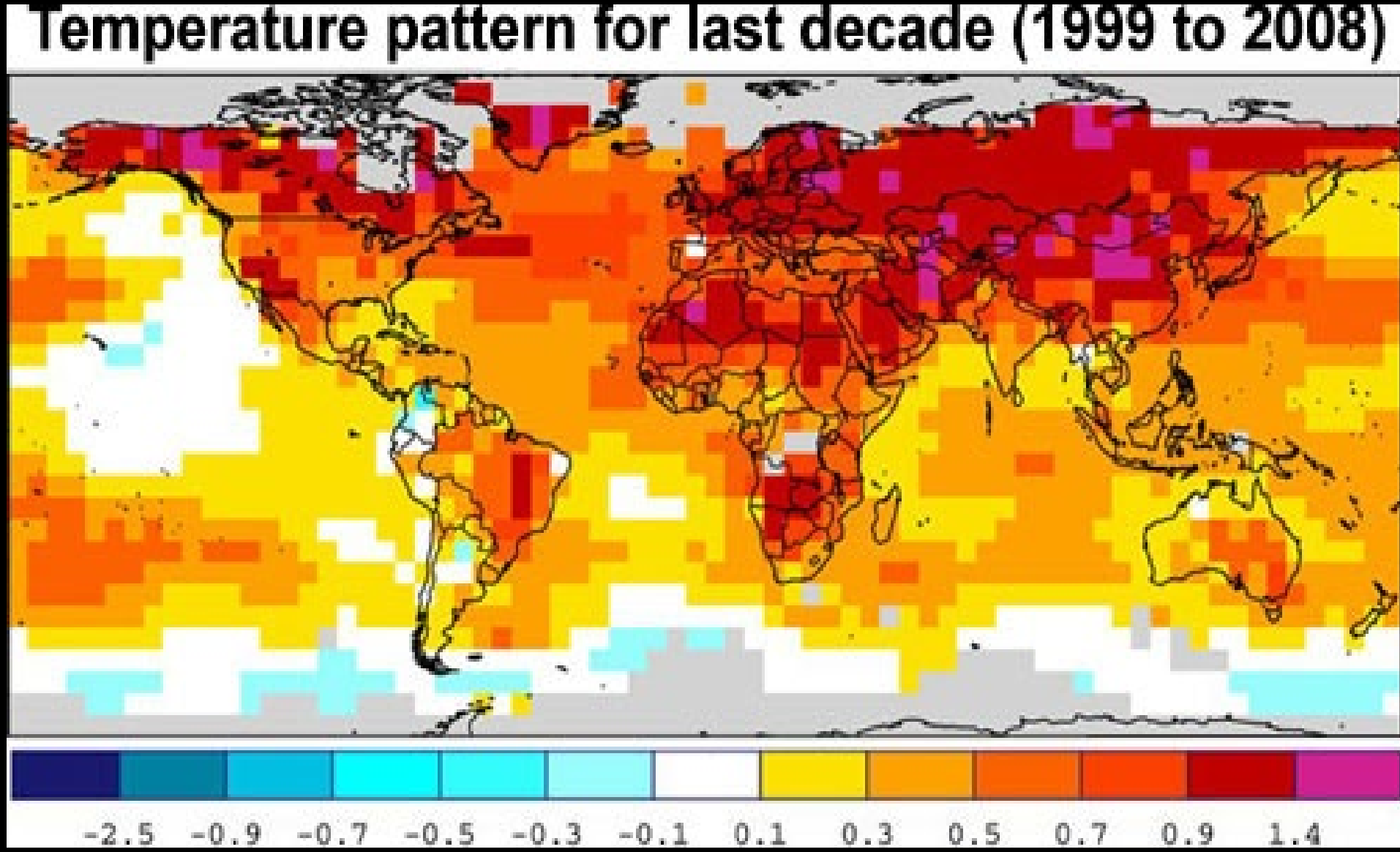
The Medieval Warm Period – MWP

- **By far the most comprehensive study of past 2,000 years' temperatures is the PAGES collaboration of 78 researchers published in Nature: Geoscience in 2013… they find**:
- Warm periods were not sych'ed around the world. But still, even **globally averaged**, it was slightly warmer for a few hundred years than it was a few centuries before, or after. Globally, **MWP likely cause: fewer volcanic eruptions, and higher solar activity and luminosity as revealed by atmospheric isotope data. (solar wind affects cosmic ray impacts on our atmosphere, seen in C^{14}/C^{12} ratio, Be^{10})**
- *"The period from around AD 830 to 1100 generally encompassed a sustained warm interval in all four Northern Hemisphere regions. In South America and Austral-Asia, a sustained warm period occurred later, from around AD 1160 to 1370."*
- *"Our regional temperature reconstructions also show little evidence for globally synchronized multi-decadal shifts that would mark well-defined worldwide MWP and LIA (Little Ice Age) intervals.*
- *Instead, the specific timing of peak warm and cold intervals varies regionally, with multi-decadal variability resulting in regionally specific temperature departures from an underlying global cooling trend."*

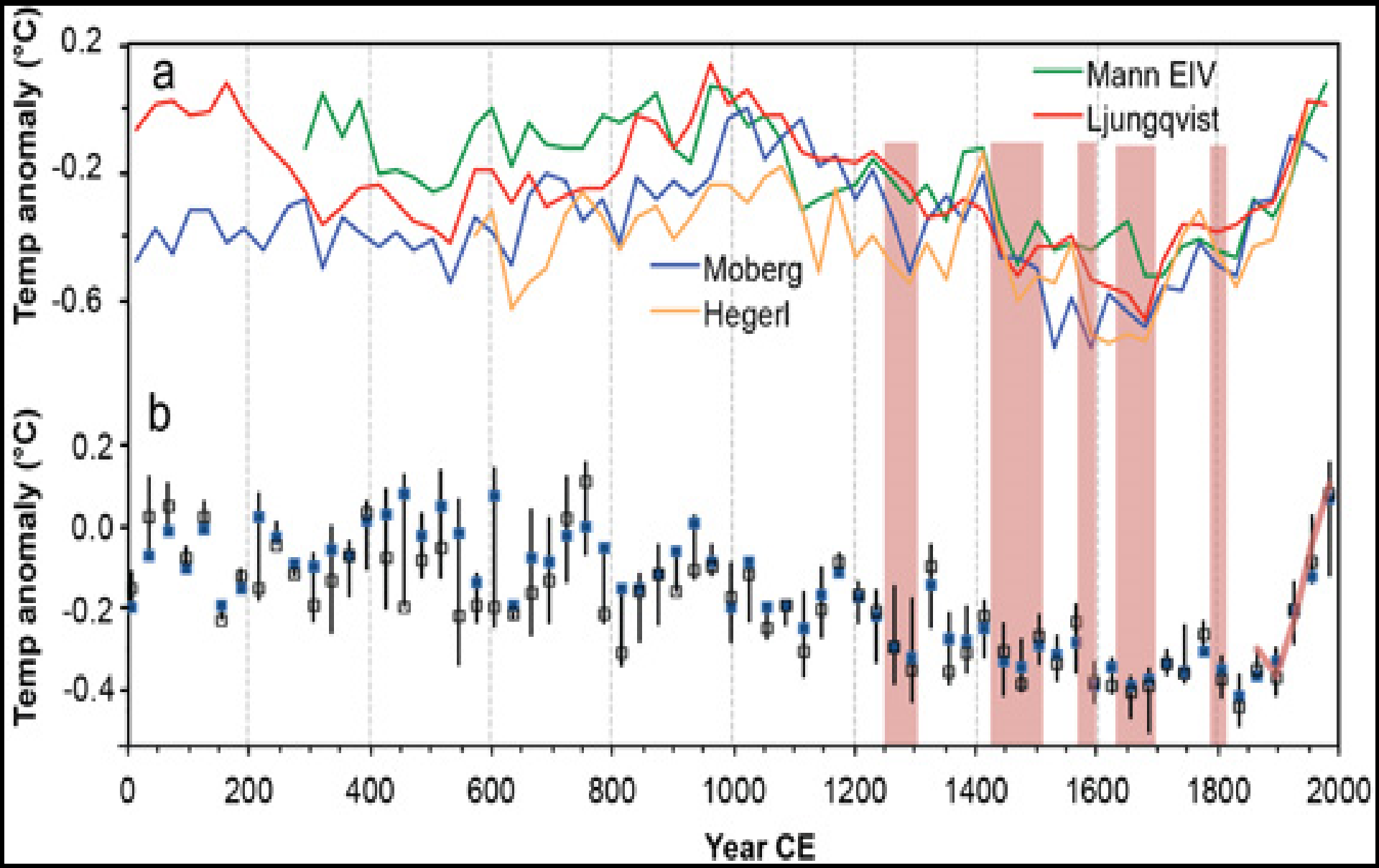
MWP: Regionally Varied, mostly northern hemisphere especially North Atlantic (Greenland, Iceland) and Northern Europe. Little seen globally, especially compared to…



… Today. Much Hotter



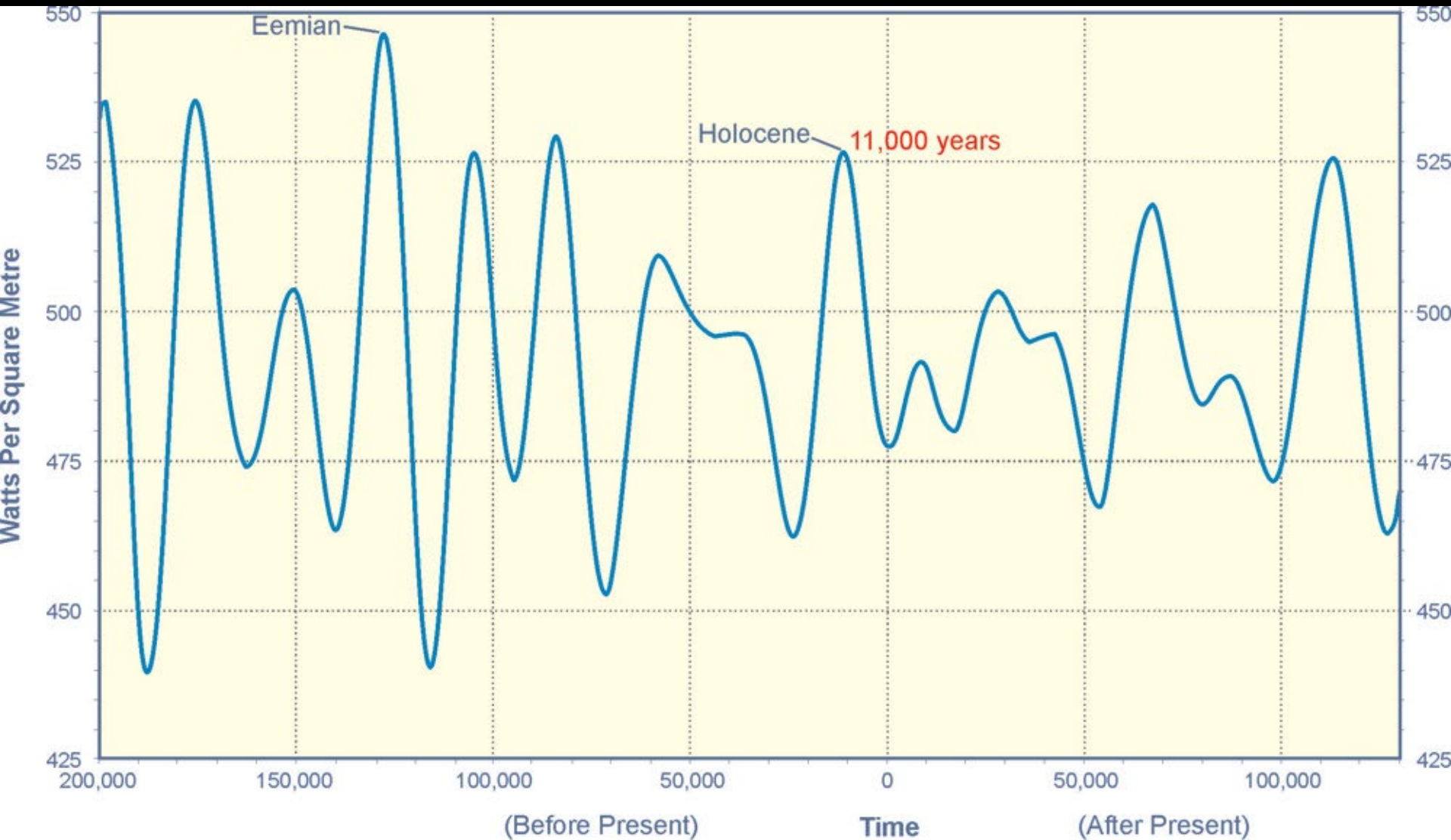
(a) Top: Earlier Published Studies. (b) bottom: PAGES synthesis of Most Recent and Comprehensive Data (2013) Shows Almost No Global Medieval Warm Period.



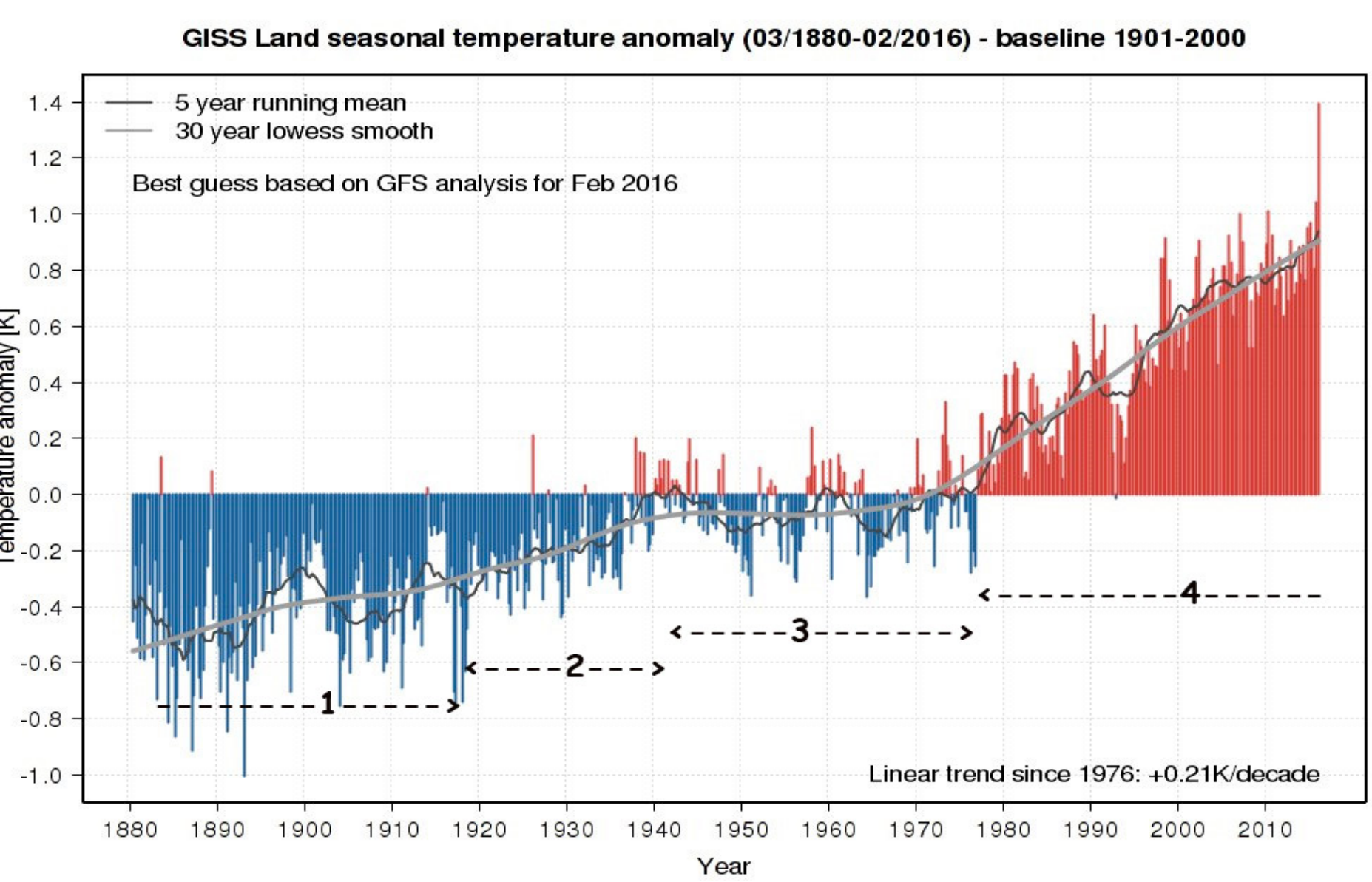
Except for MWP, long term temps were slightly declining until the Fossil Fuel Era

- Recall MWP causes: Volcanics quiet, higher solar luminosity as revealed by solar-wind induced isotope changes)
- The past 2,000 years shows a flat to slightly down trend in global temperatures, which is consistent with the Milankovitch forcing during this period (next slide)
- Then, the **Fossil Fuel Era** of the past century, which is marked by rapid global temperature rise.

Milankovitch Cooling - Past 11,000 Years. Today=0 on Graph



The GISS Global Temperature Record for the past ~150 Years Can Be Roughly Divided into 4 Regimes. (Adopted zero baseline here is the 20th century average)



Global Surface Temperatures: Reference Standards

- There is needless confusion from inconsistent reference standards.
- Widely regarded as most relevant and reliable is the NASA GISTEMP Goddard Institute for Space Sciences data which corrects for missing weather stations (Arctic, Sahara, etc) to get a true global average. Theirs is the data I try to always present.
- The “pre-industrial baseline” has been conventionally the average GISS temperatures from 1880 to 1910, since 1880 is the earliest year of reliable fairly comprehensive global surface temperature data. We can do better now…

A Better Determined Pre-Industrial Baseline from Michael Mann Collaboration

- Michael Mann (**Schurer, Mann, *et al.* 2017** and here, discussed here) argues that we should go back to true pre-fossil fuel times for true "pre-industrial" since coal burning was already relevant in 1880, and CO2 emissions were already 10% of today's at the beginning of the 20th century.
- *"The NASA (GISS temperature) anomaly is considerably higher than the anomaly reported by NOAA. This reflects the fact that NASA's calculations are tuned to account for temperature changes at the poles, where there are far fewer monitoring stations. NOAA relies only on historical station data and makes no adjustment to account for sparse records at the poles, where warming has been more rapid relative to non-polar regions." (Sci Am source)*

Reference Temperature Choices

- The IPCC, unfortunately, chose to quote temps relative to the 1951-1980 average: Certainly NOT "pre-industrial"! Using the most reliable (NASA GISS) temperatures, we then have the following calibrations, easily calculated using the yearly GISS data you can get from their website:
- (20th Century average) - (IPCC)= **-0.025 C**
- ("Pre-industrial"=1880-1910 avg) – (IPCC) = **-0.254 C**
- So, to correct IPCC temperature anomalies quoted from the 20th century avg baseline into "1880/1910 pre-industrial" temps=> (20th Century avg) – (1880/1910 pre-indust) = **-0.28 C**

But the True Pre-Fossil Fuel Era Average Temperature is Lower

- **Schurer *et al.* 2017** find true pre-industrial temperatures (1400-1800 average) were 0.13C cooler than the 1850-1900 average (see later graph), and **0.20C cooler than the 1880-1910 average based on their range of GHG models (see their text).**
- Including this additional 0.2C then says: (20th Century avg) – (Schurer Pre-Industrial) **= -0.48 C . So we need to add 0.48C to GISS website global average surface temperature**

GHG Induced Temperatures were 0.2C Cooler During 1400-1800 avg *vs*. the Conventional 1880-1910 avg (Schurer *et al.* 2017)

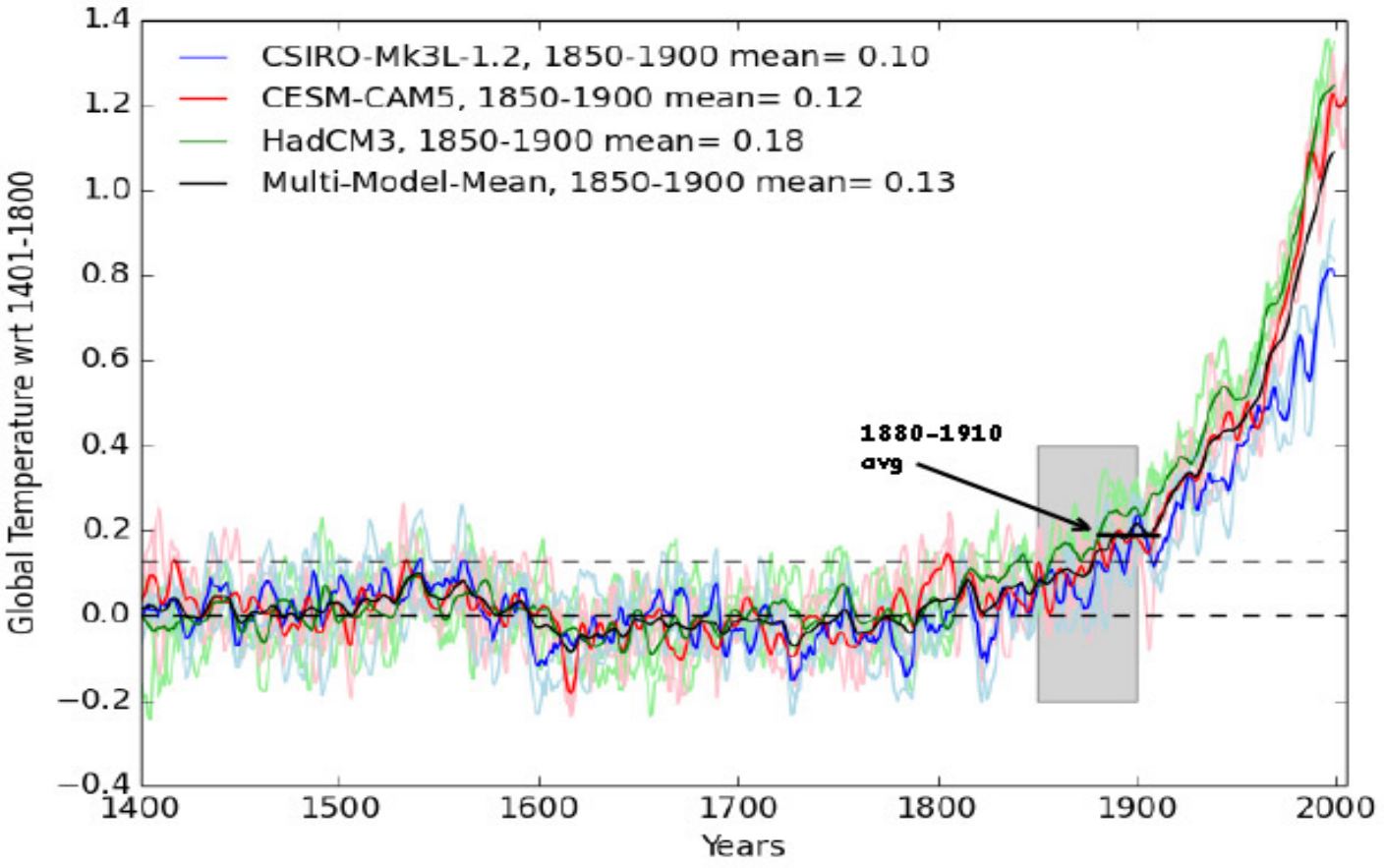
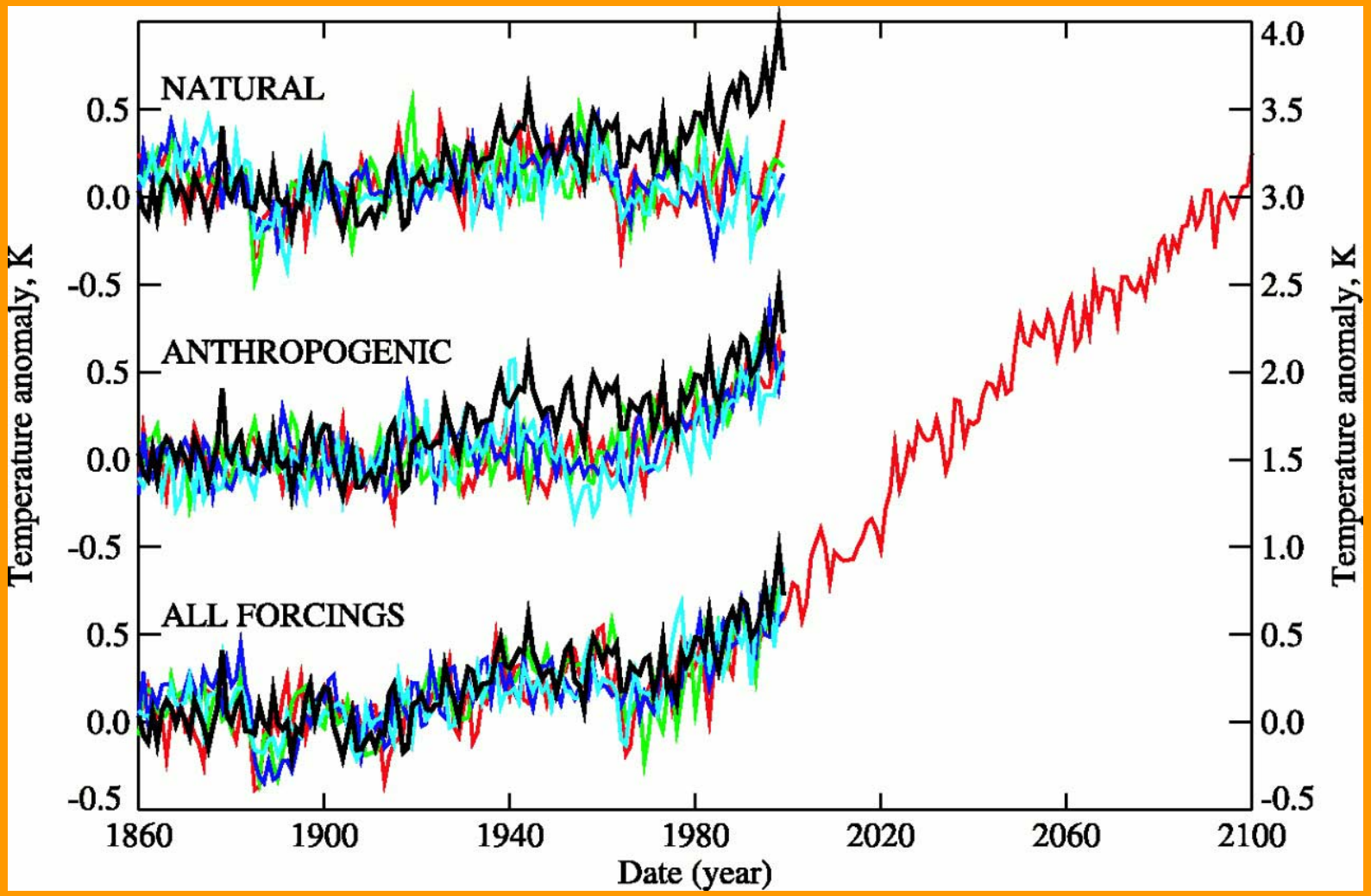


Fig S1- Temperature response to Greenhouse Gas forcing Global mean temperature for three models, smoothed by a 5-year running mean, details given in table S1. Bold coloured lines model means, light coloured lines individual ensemble members. Black line multi-model mean. 1851-1900 highlighted by grey box. Mean for this period shown in legend for the different models and multi-model mean for this period is highlighted by a horizontal dashed line.

"Pre-Industrial" however, may not be the right baseline to consider.

- What we really want to know is: **how hot is today's global average surface temperature compared to the temperature we'd have had TODAY in the absence of humans?**
- **Stott *et al.* 2009** , find that the variation in global average surface temperature due purely to non-human causes was near zero during the 20th century to 2005, relative from the 1881-1920 average (see "Natural" colored lines on next graph). So, numerically, it turns out these two conceptually different baselines are about the same.

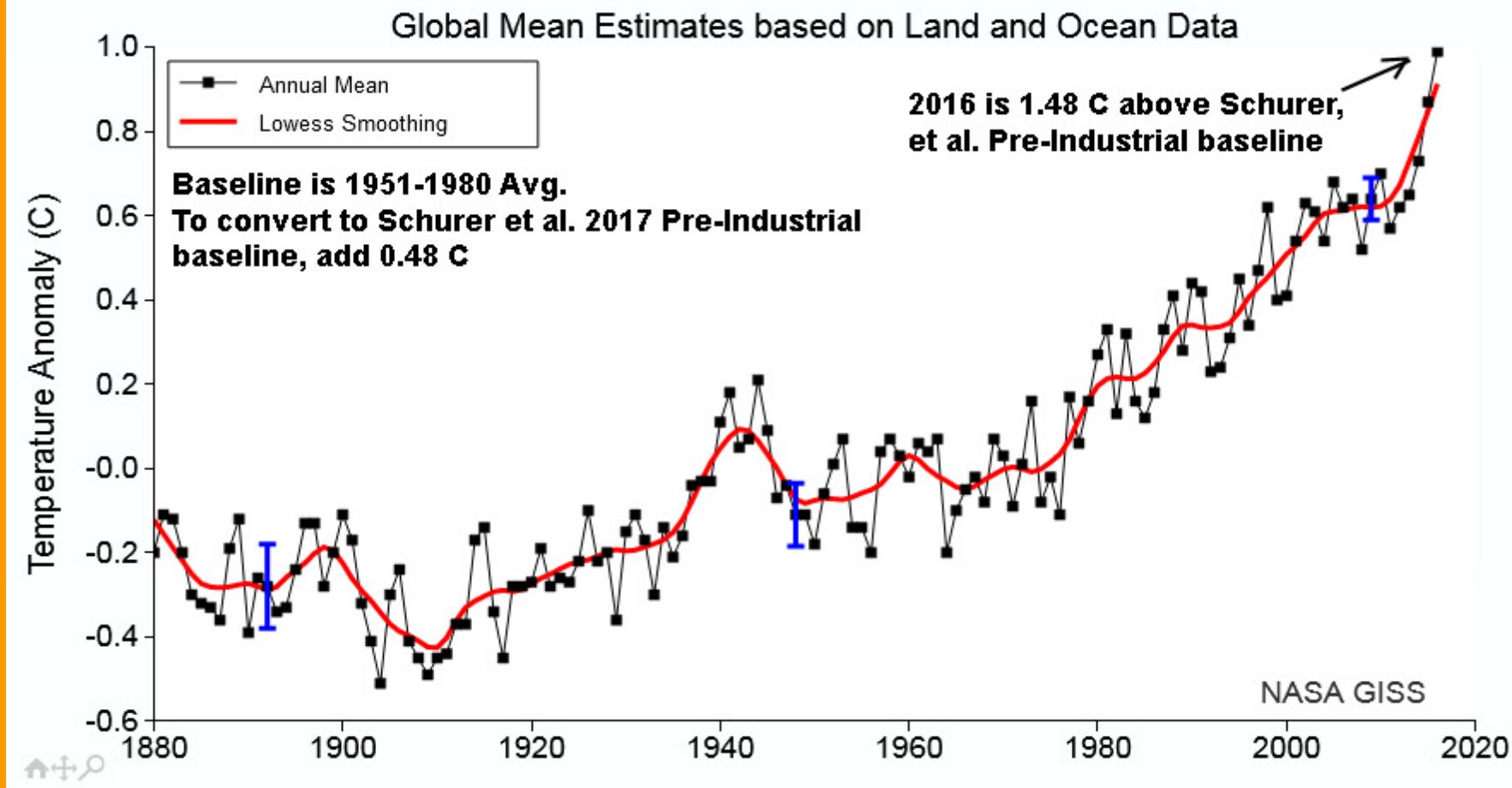


"Annual-mean global mean near-surface (1.5 m) temperature anomalies (relative to 1881–1920) for the NATURAL, ANTHRO, and ALL ensembles. Ensemble members are shown as colored lines." (Stott et al 2009)

Here's the corrections to apply to nominal GISS temperatures to refer them to the various baselines seen, in table below

GISS Calibration from (first baseline) – to – (second baseline)	Correction to Apply
(1951-1980 Average) – to – (20th Century Average)	Add 0.025 C
(1951-1980 Average) – to – (1880-1910 "Pre-Indus")	Add 0.254 C
(20th Century Average) – to – (1880-1910 "Pre-Indus")	Add 0.28 C
(1880-1910 "Pre-Indus") – to – (Schurer *et al.* "Pre-Indus")	Add 0.2 C
(1951-1980 "Pre-Indus") – to – (Schurer *et al.* "Pre-Indus")	Add 0.48 C

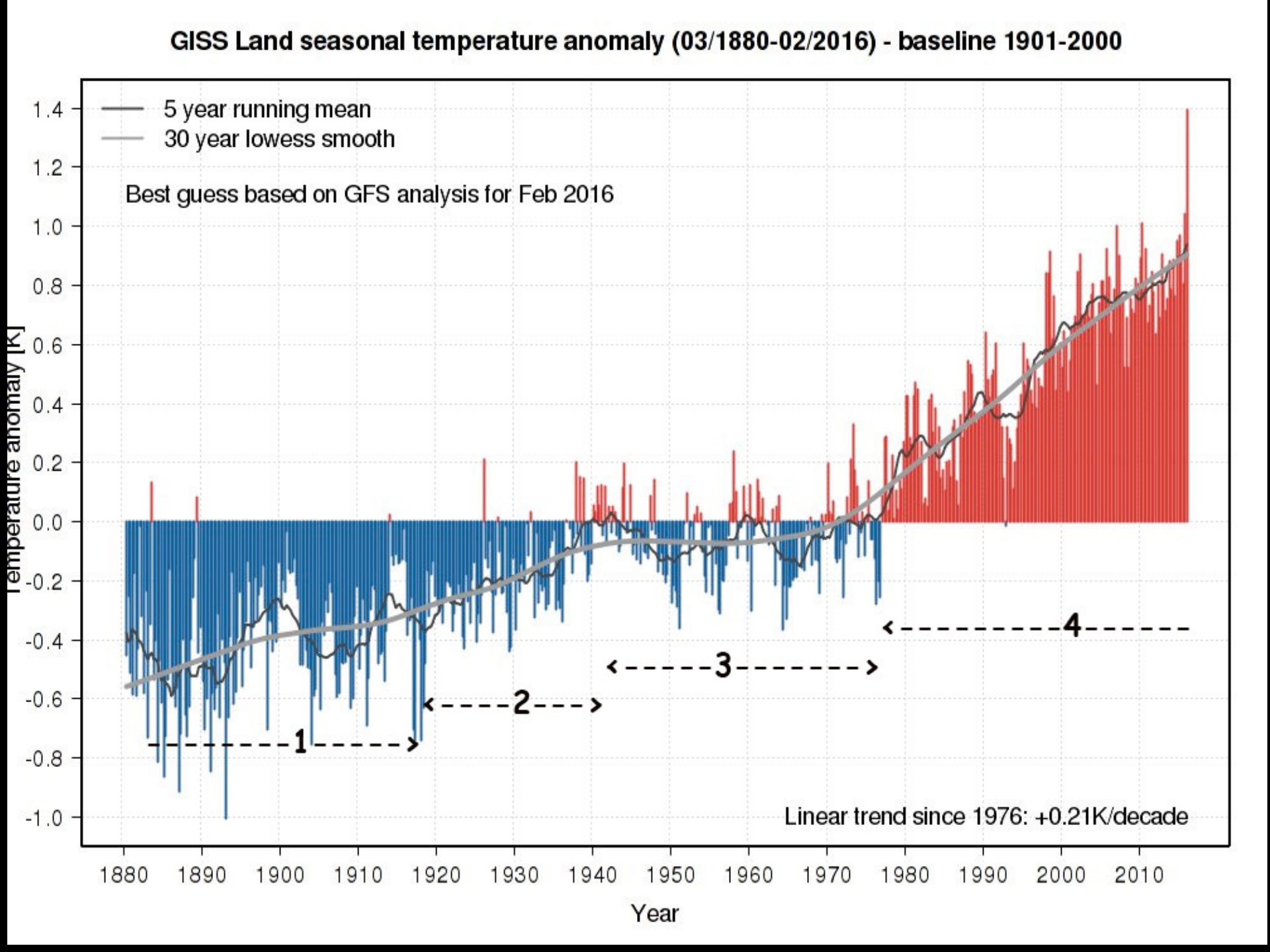
The NASA GISS global average 2016 temperature was +1.00C above the 1951-1980 baseline = 1.28C above the 1880-1910 Pre-Industrial Baseline, and = 1.48C above more realistic Schurer *et al.* (2017) Pre-Industrial baseline).



Land-ocean temperature index, 1880 to present, with base period 1951-1980. The solid black line is the global annual mean and the solid red line is the five-year lowess smooth. The blue uncertainty bars (95% confidence limit) account only for incomplete spatial sampling. [This is an update of Fig. 9a in Hansen et al. (2010).]

Now Let's Look at Global Temperatures, broken into 6 Time Periods Since 1880 According to the Different Forcings.

Start with Period #1:

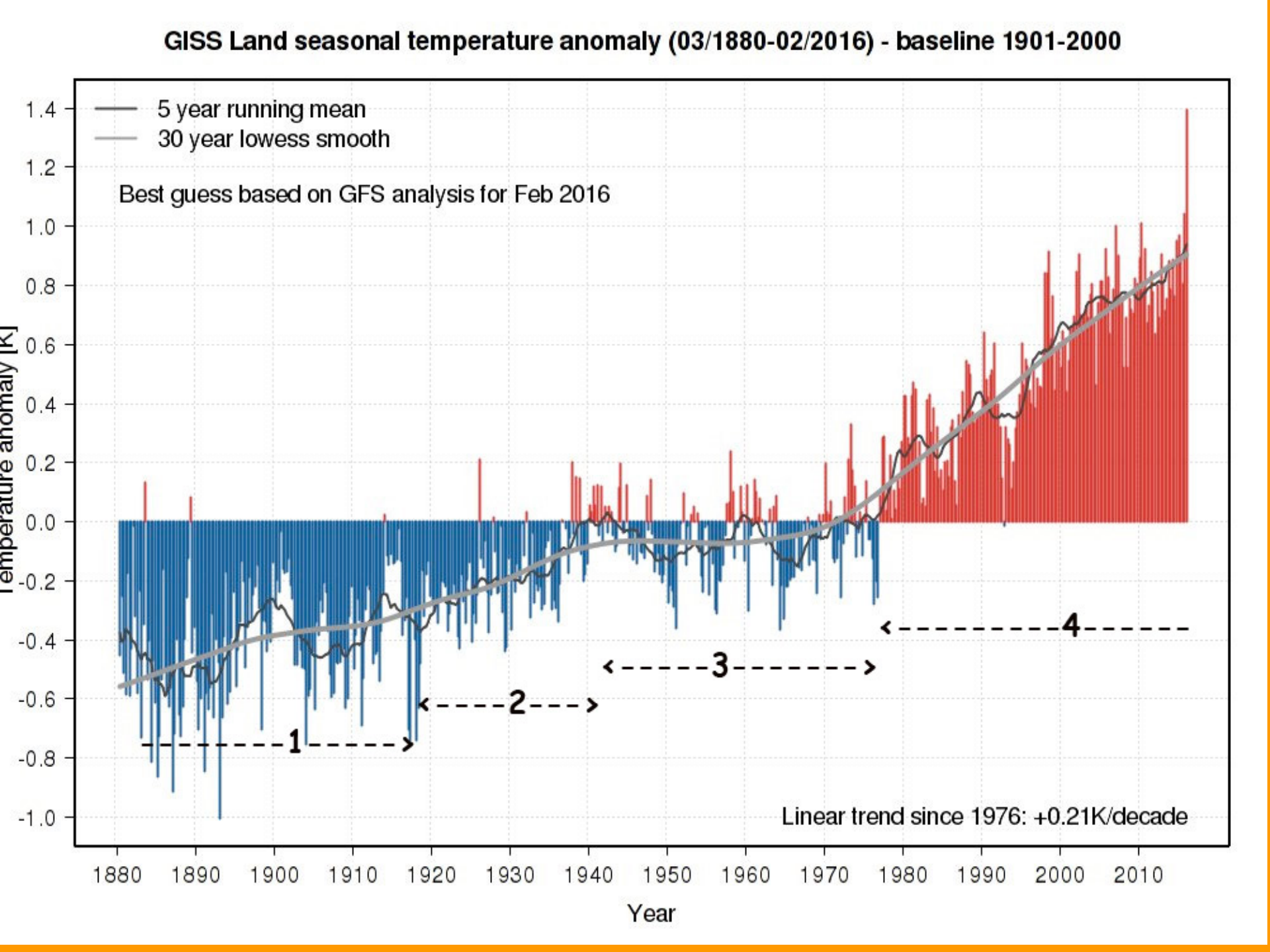

GISS Land seasonal temperature anomaly (03/1880-02/2016) - baseline 1901-2000
5 year running mean
30 year lowess smooth
Best guess based on GFS analysis for Feb 2016
Temperature anomaly [K]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
1
2
3
4
Linear trend since 1976: +0.21K/decade
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

Period #1. 1880~1912: Slight Cooling

- At this time, human generated GHG's are still fairly small. Industrial coal widely used, but cars are a rarity, human population is ~10% of today's. Coal aerosols?
- This is still in the general regime of the past interglacial ~6,000 years, which shows little trend in global temperatures

Volcanic Stratospheric Sulfate-induced Cooling

- While the 1850-1900 period was closely average *vs* the 1400-1800 time period as far as major volcanic eruptions, the last 1/3 of this period included **Krakatoa 1883** (climatically strongest in modern record, see especially **Gleckler *et.al.* 2006**), **Santa Maria** (1902, one of the 5 biggest of the past 200 years), then **Katmai 1912** (largest of the 20th century). These added aerosol cooling
- The Katmai eruption set the minimum for global temperatures for the 20th century (and very likely for millennia beyond)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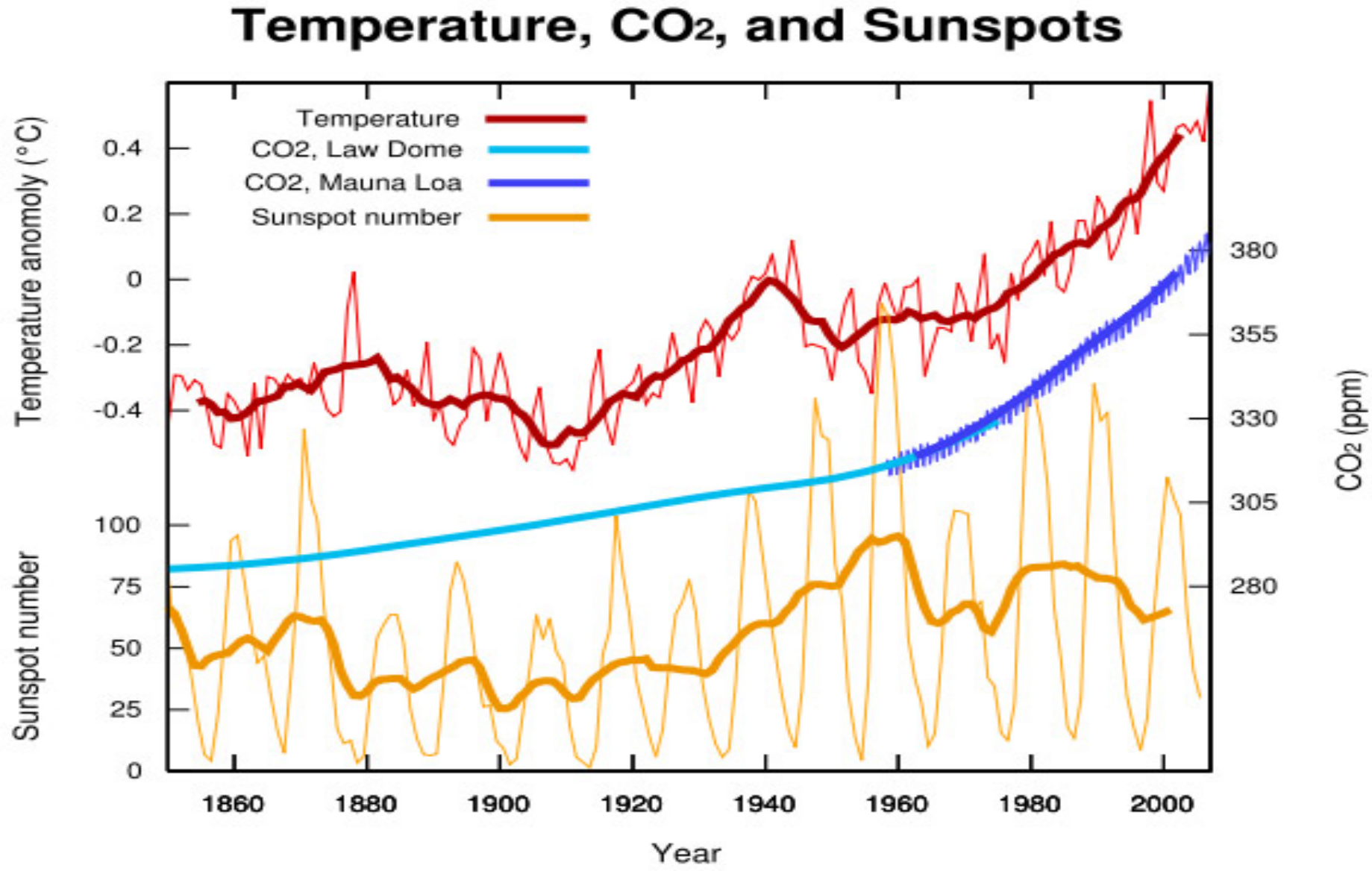
Period #2: ~1912 to ~1942: Rising Global Temperatures

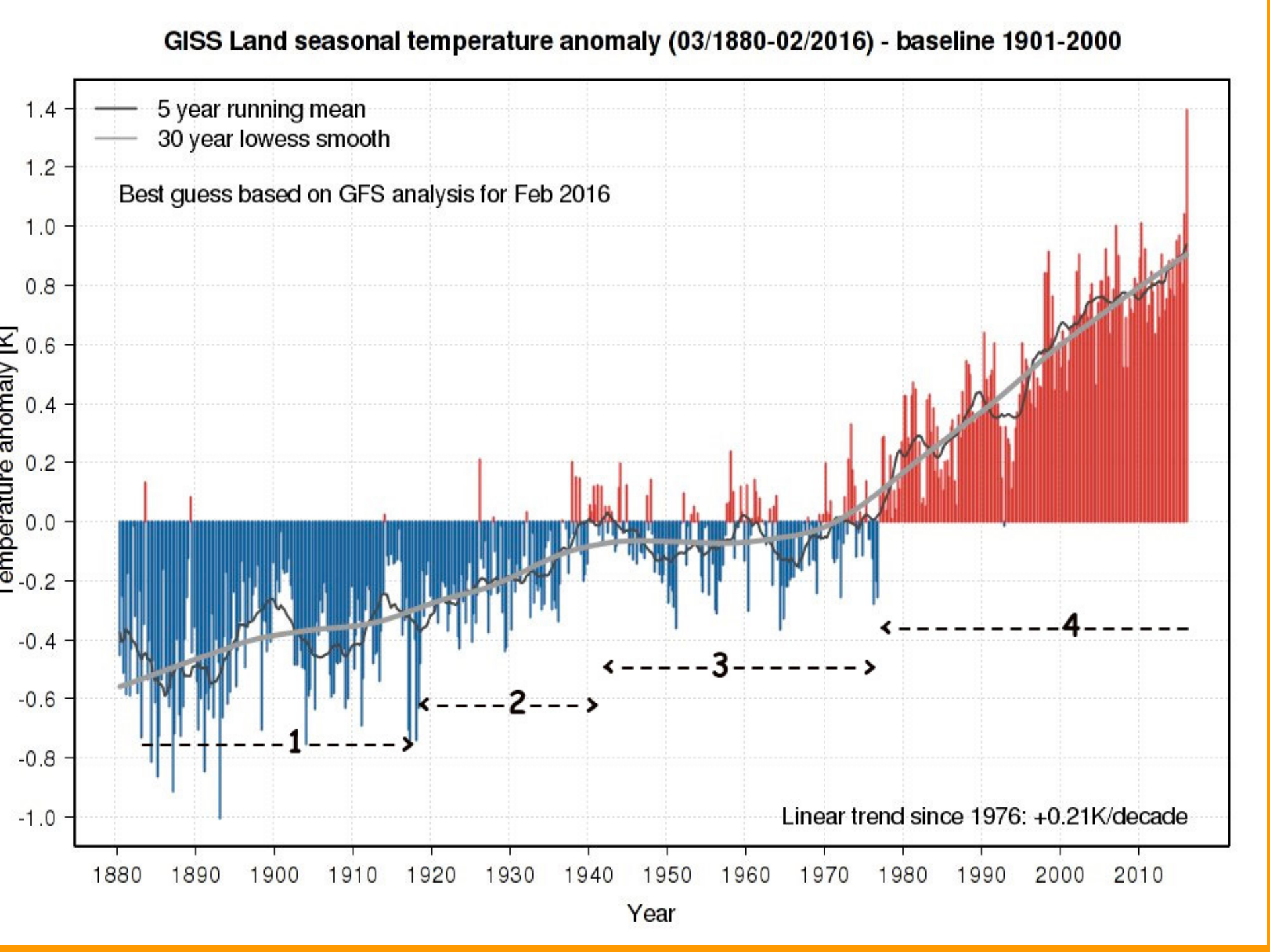
- Climate modelling finds this was due to a combination of both human and natural warming climate effects. **Here are the 5 most dominant**
- **1.** The most important effect is likely the warming phase of the Pacific Decadal Oscillation (see 4 slides ahead). This warming phase lasted from about 1920 to the powerful El Nino of 1942.
- **2.** Rising CO2 levels from the Industrial Age (see next slide), which became large enough to be climatically large late in this period. Anthropogenic aerosol-caused cooling *e.g.* coal burning are significant before this period, however.
- **3.** This was a quiet period of **no significant volcanic eruptions to** inject natural cooling aerosols, compared to the 1883-1912 period.

Also Rising Solar Activity and Rising Deforestation

- **4.** Long term show a modulation such that successive solar maxima are roughly similar, but rise and fall over roughly century time scales
- Sunspot numbers are a fairly good proxy for solar activity, and recall that there is a 0.1% modulation in the solar luminosity with the solar cycle, and **stronger solar cycles are associated with higher solar luminosity**
- During this period, solar sunspot maxima were trending higher, and the inferred solar luminosity was rising (we have no direct measurements of solar luminosity back in those days)
- **5.** This was a period of rapid population growth and accompanying deforestation. Even today, deforestation contributes about ¼ of human CO2 emissions, and was likely as strong back in this period.

Climate modelling (*e.g.* Hansen 2005) shows increasing solar activity and accompanying luminosity rise likely account for 1900-1945 global temperature rise, together with rising CO2 and lower volcanic activity. Radiative forcing amount is not shown on these graphs.

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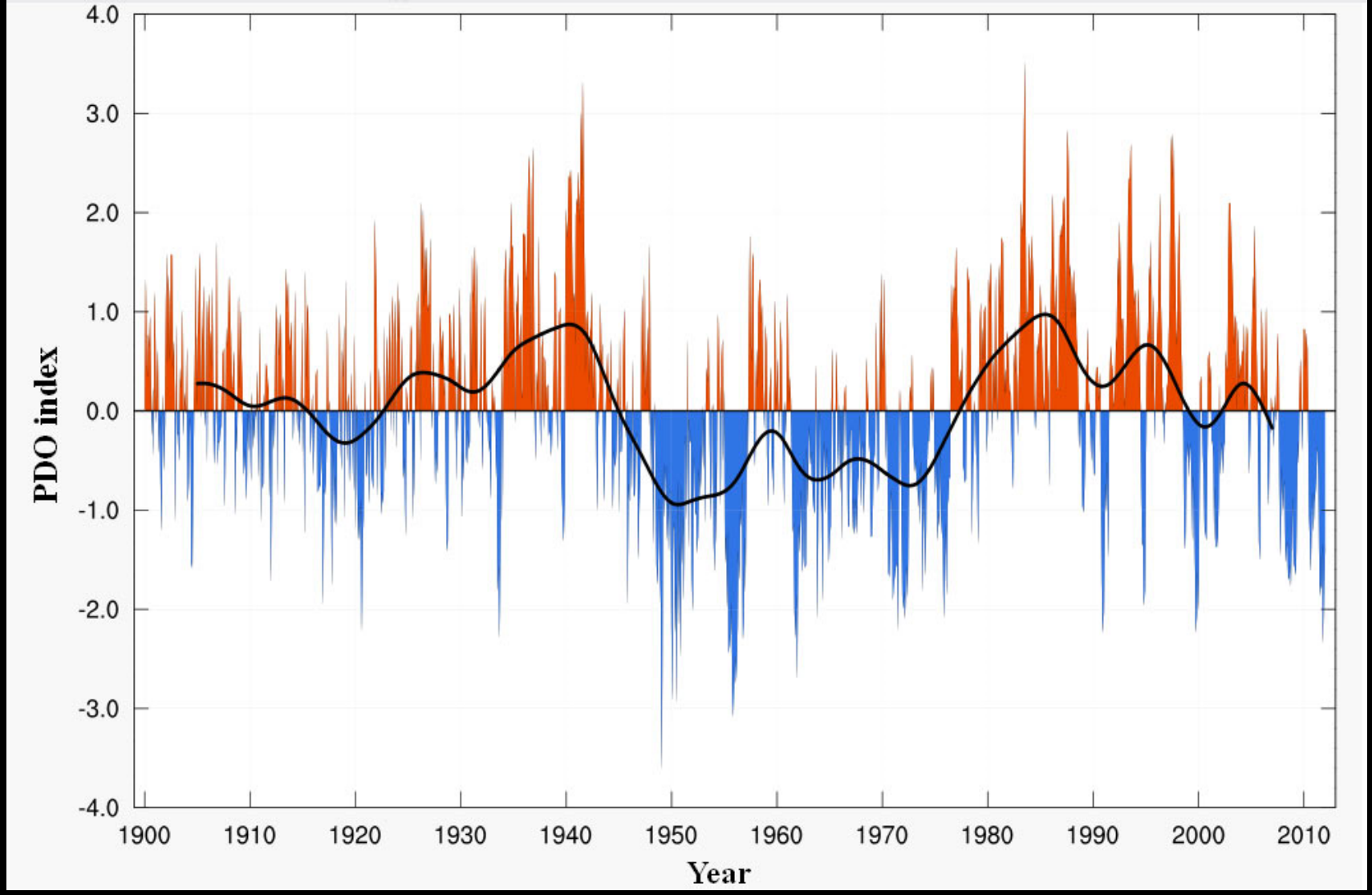
2010
Year

Period #3: 1945-1975 – A Cool Period in the Pacific Decadal Oscillation

- The **Pacific Decadal Oscillation** (PDO) is a relatively long term oscillation in the heat transport going from the shallow to the deep Pacific ocean.
- When heat is transporting from shallow to deep levels, the shallow surface waters tend to be cooler (another way to think of it, is that the upwelling of colder waters is more effective).
- Colder surface waters tend to pull heat from the atmosphere to the ocean, and, other things being equal, would correspond to cooler global air temperatures.
- The Pacific is large, and this oscillation between relatively warmer and cooler surface waters is irregular but of order a decade or two…
- Note on the PDO slide to follow – the mid-century halt in global warming corresponds to a cool period in the PDO. **This is as important, or even more so than the aerosol cooling we now discuss…**



The PDO Index for the past century. The PDO is a significant influence on global temperatures, but provides only an OSCILLATING forcing, which in the temperature data is seen superimposed upon the SECULAR (i.e. not oscillating) rise due to the SECULAR rise in greenhouse gas emissions.

Aerosol Smog Grew Rapidly in Period #3

- Post WWII period of rapid rebuilding, industrialization.
- While CO2 levels are rising, not rising as fast early in this period. What is rising faster is the pollution aerosols associated with coal burning, rising vehicle-miles, and power plants.
- Unburned hydrocarbons, catalyzed by sunlight and water, combine with sulfates to produce reflective sulfuric acid droplets and other sulfates aerosols reflecting incoming sunlight and cooling the Earth. Recall this is the **aerosol direct effect**
- Plus the so-called **aerosol indirect effect** - These particles are also large enough to act as cloud nucleation sites and increase low clouds since this air pollution usually hangs low to the ground due to temperature inversions. Low clouds, recall, generally cool Earth surface temperatures by reflecting sunlight and having warm cloud tops effectively radiating heat to space
- You young'uns who grew in in clean air can't believe how bad it was back then. I grew up near LA and often you couldn't see even a mile or two miles through the eye-stinging smog.

More Man-made Pollution, Less Sunlight hits the Ground

- At the same time, World War II destroyed a lot of life and industrial capability, and it took some time for this to be rebuilt. So there was a period of reduced growth in greenhouse gases during WWII itself, as seen on the CO2 curve shown earlier.
- Also, the rising solar luminosity (as inferred from the sunspot cycle) came to a top in the mid 1950's and has been declining slowly ever since.
- By later in this period ('60's) much higher anthropogenic reflective sulfate smog and a halt in solar luminosity increase was enough to counterbalance CO2-induced global warming and keep temperatures roughly constant

The Pennsylvania Smog of 1948

London Smog 1952, killed 12,000 people

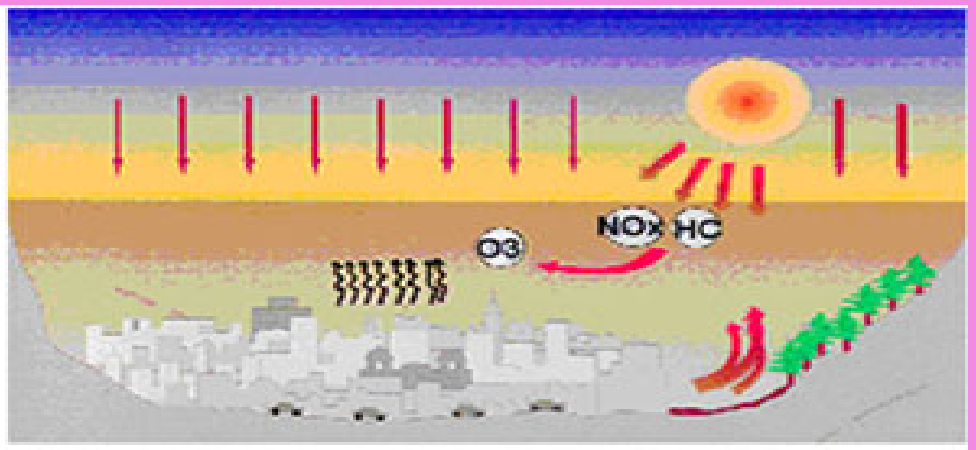
London – THE Smog Capital of that Time

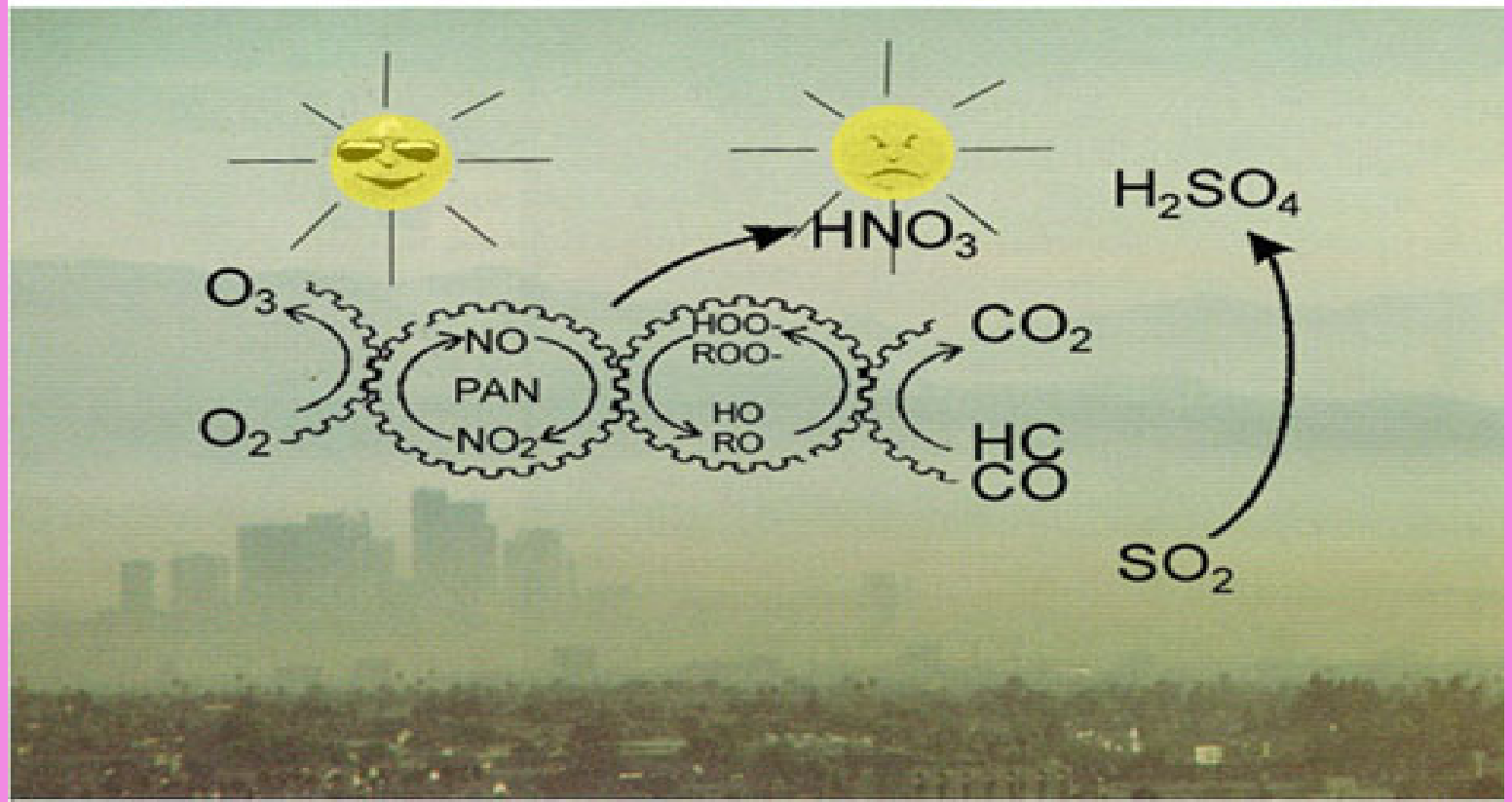
But L.A. Provided Strong Competition

New York – Not Much Better

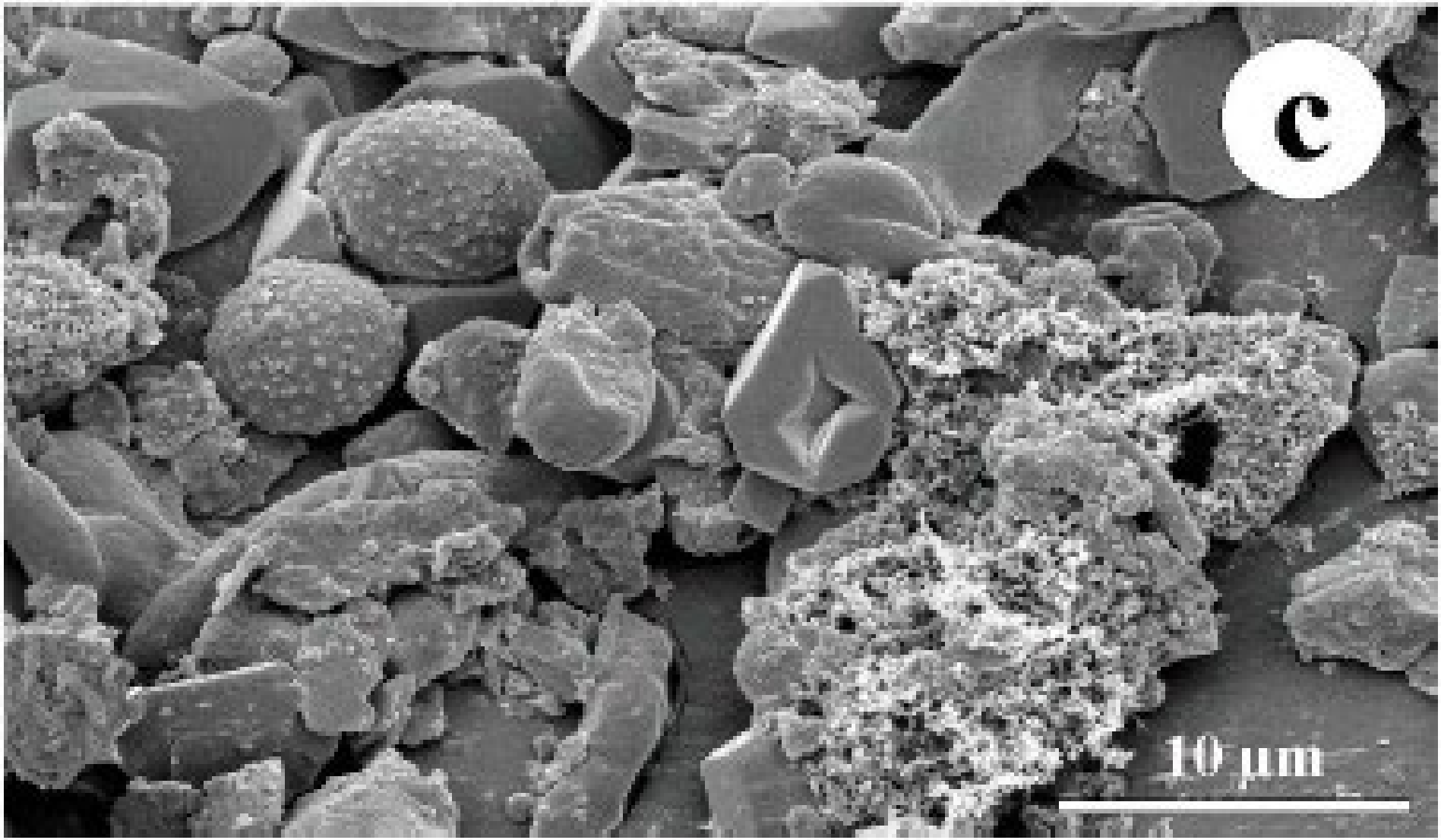
The Smog Machine

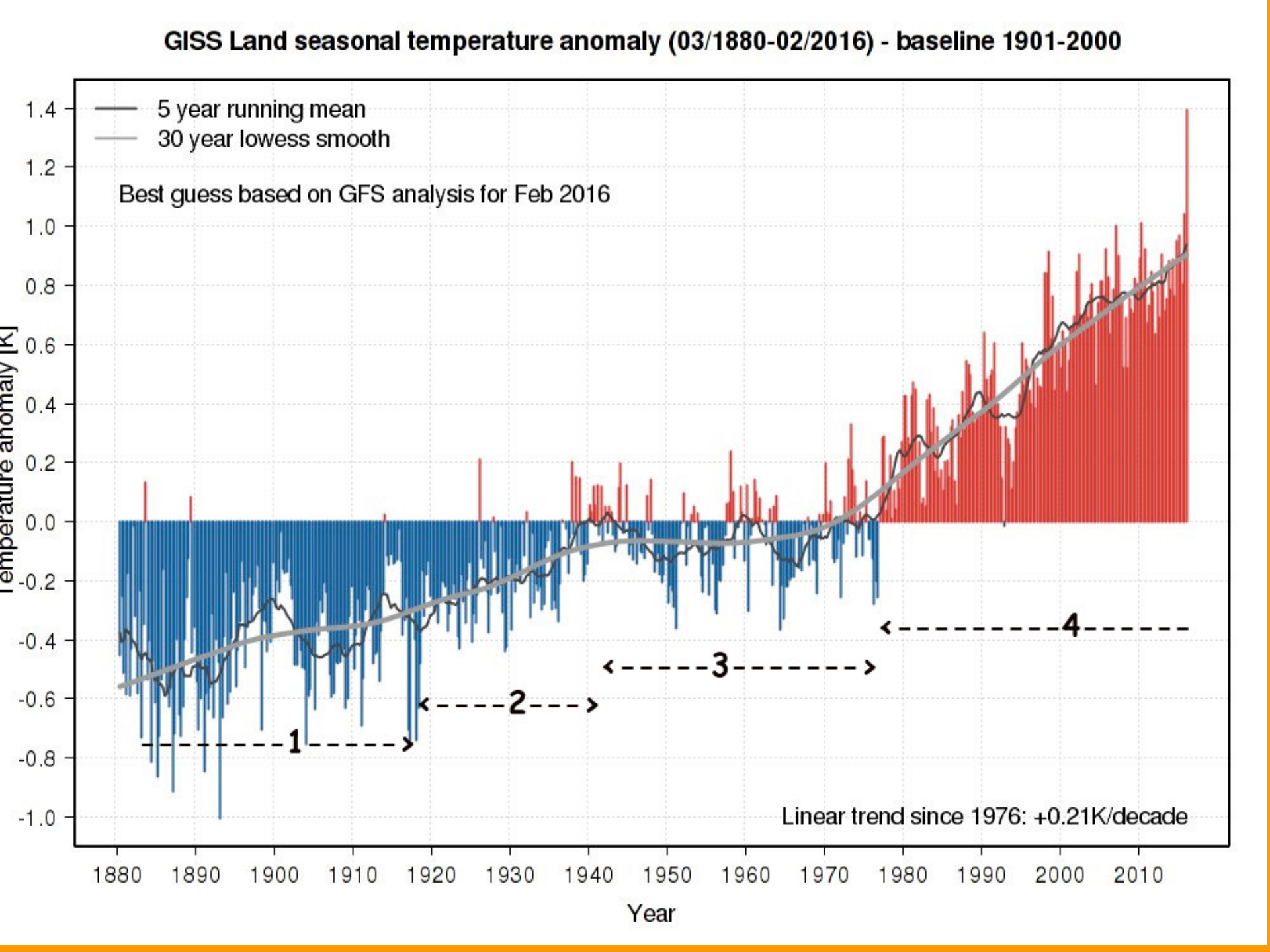
The
Smogmachine





Smog Particles –from R. Healy (looks like a couple of pollen grains (rounded) at upper left as well)



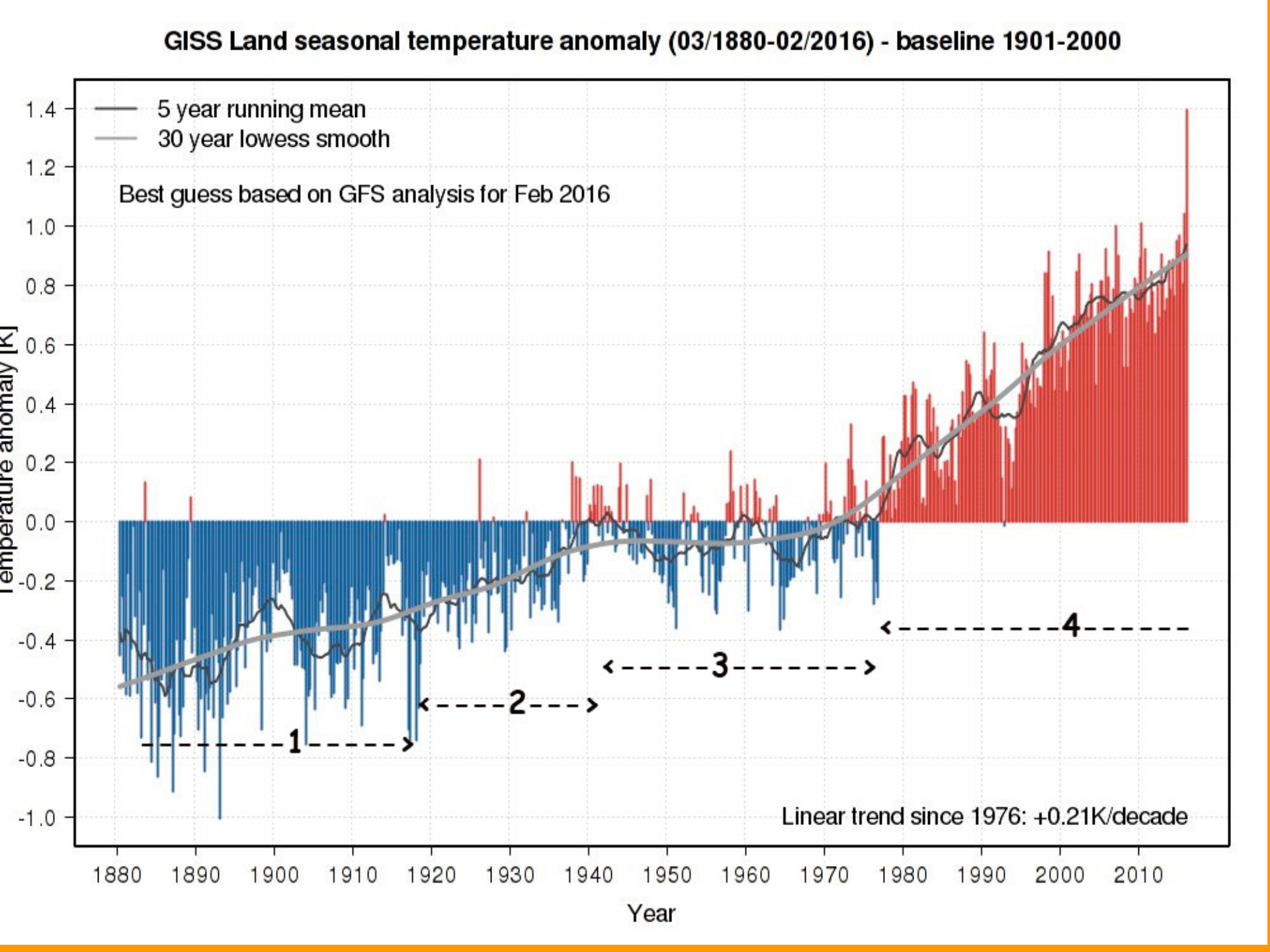

GISS Land seasonal temperature anomaly (03/1880-02/2016) - baseline 1901-2000
5 year running mean
30 year lowess smooth
Best guess based on GFS analysis for Feb 2016
Temperature anomaly [K]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
1
2
3
4
Linear trend since 1976: +0.21K/decade
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

Period #4. ~1970 to ~2000

- The Clean Air Act of 1970 and other air pollution laws in the U.S. and Europe cause a significant **reduction in cooling aerosols, adding heat forcing to climate.**
- China and Asia are not yet ramped up to significant industrialization and coal-fired pollution. That comes after 2000.
- Net global aerosol effect is approximately a wash, as can be seen in Hansen *et al.* 2005 (later this slide set)

U.S., Europe GHG Emissions Accelerate

- Greenhouse gas emissions accelerate
- Solar and other effects are smaller compared to greenhouse gas emissions, primarily CO2 from oil, gas, gasoline, and coal burning
- **Strong and accelerating human-caused CO2 emissions, and amplifying feedback from rising humidity are greenhouse warmings which dominate climate forcings in this period.**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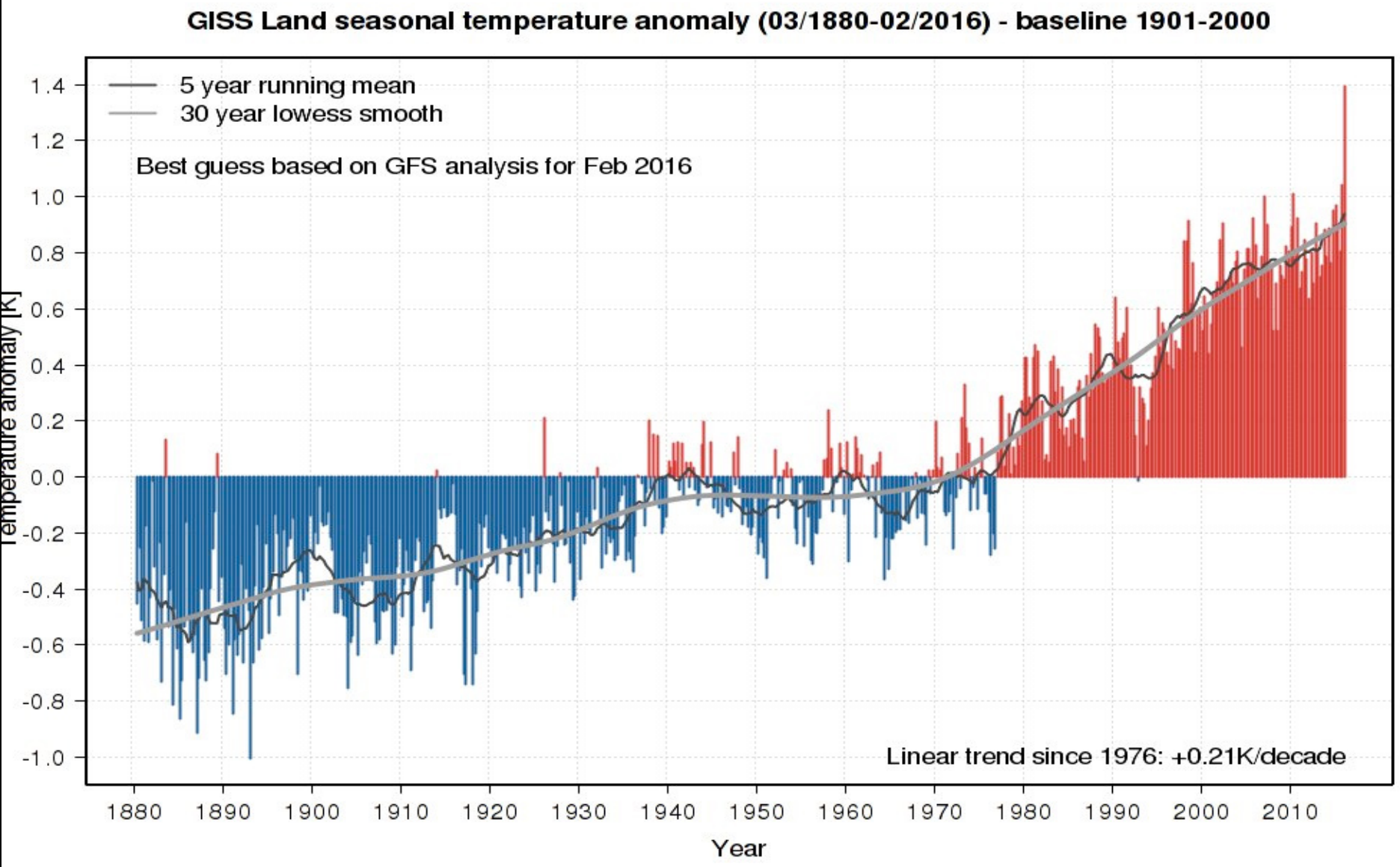
The Period 1998-2014 Also Needs Clarification: Call it Period #5

- Climate denialists claim global warming stopped at 1998 – but it has not
- 1998-2009 was the warmest decade on record.
- There were natural and man-made influences which had a cooling effect and lessened the rate of surface air temperature rise, as we'll see
- **First, the data…**

Global Avg Surface Temps (GISS) relative to 20th Century Average



Why Did 1998-2014 See A Slower Rise Rate in Global Surface Air Temperatures? There Are at least 6 Reasons:

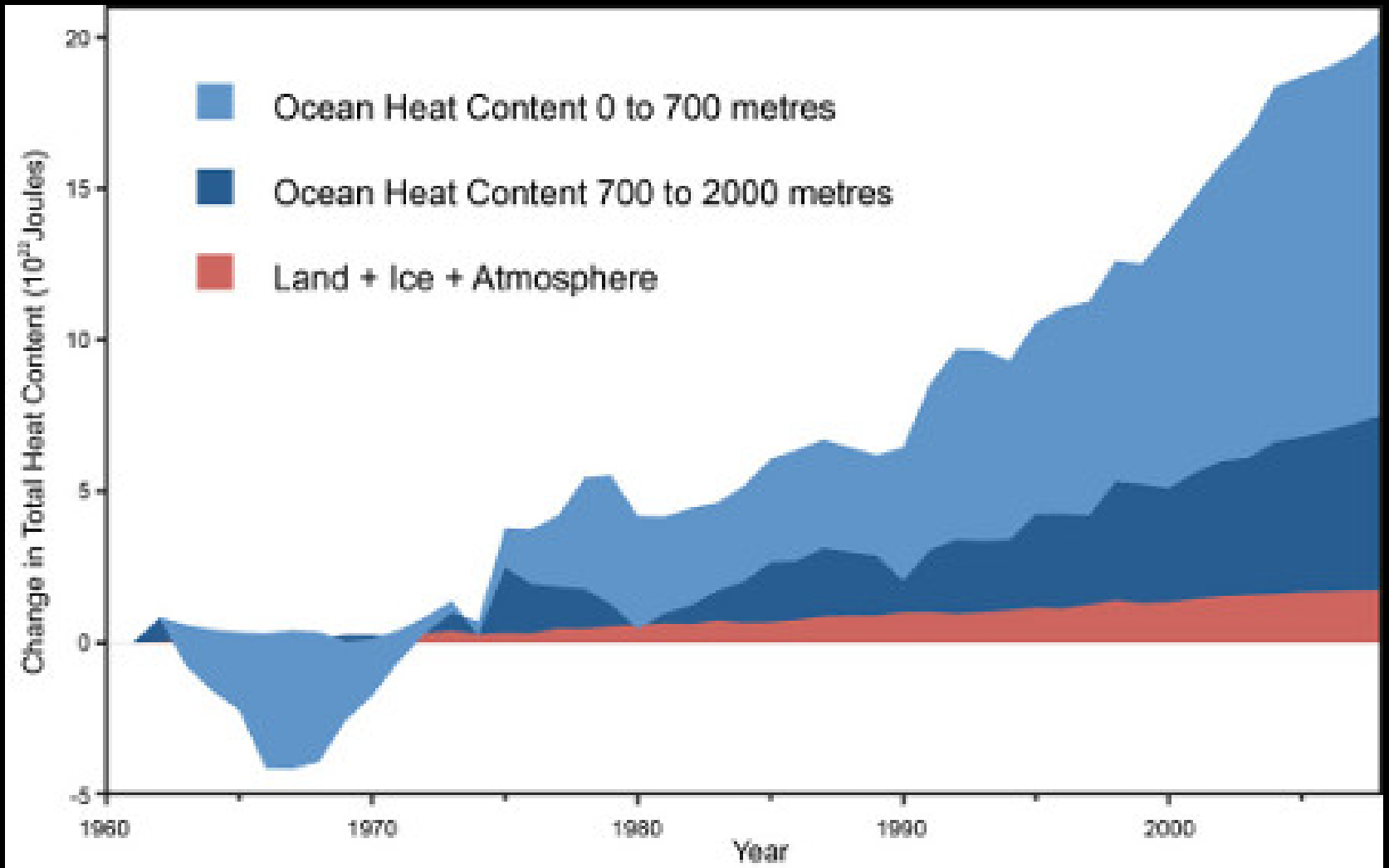
1. Cherry Picking! A practice used at every opportunity by the climate denialists. Until 2015, **1998 was the most intense El Nino on record**.

- El Nino years – hot surface water that the trade winds have piled up against Indonesia for several years, finally sloshes back eastward over the ocean surface along the Pacific equator as the trade winds weaken, halting upwelling of colder deeper water. These warm waters force the global average sea surface temperature unusually high, lowering its ability to absorb the greenhouse heat from the atmosphere.
- As one climatologist said... “OK fine, Global Warming stopped in 1998. And it started again in 1999”.

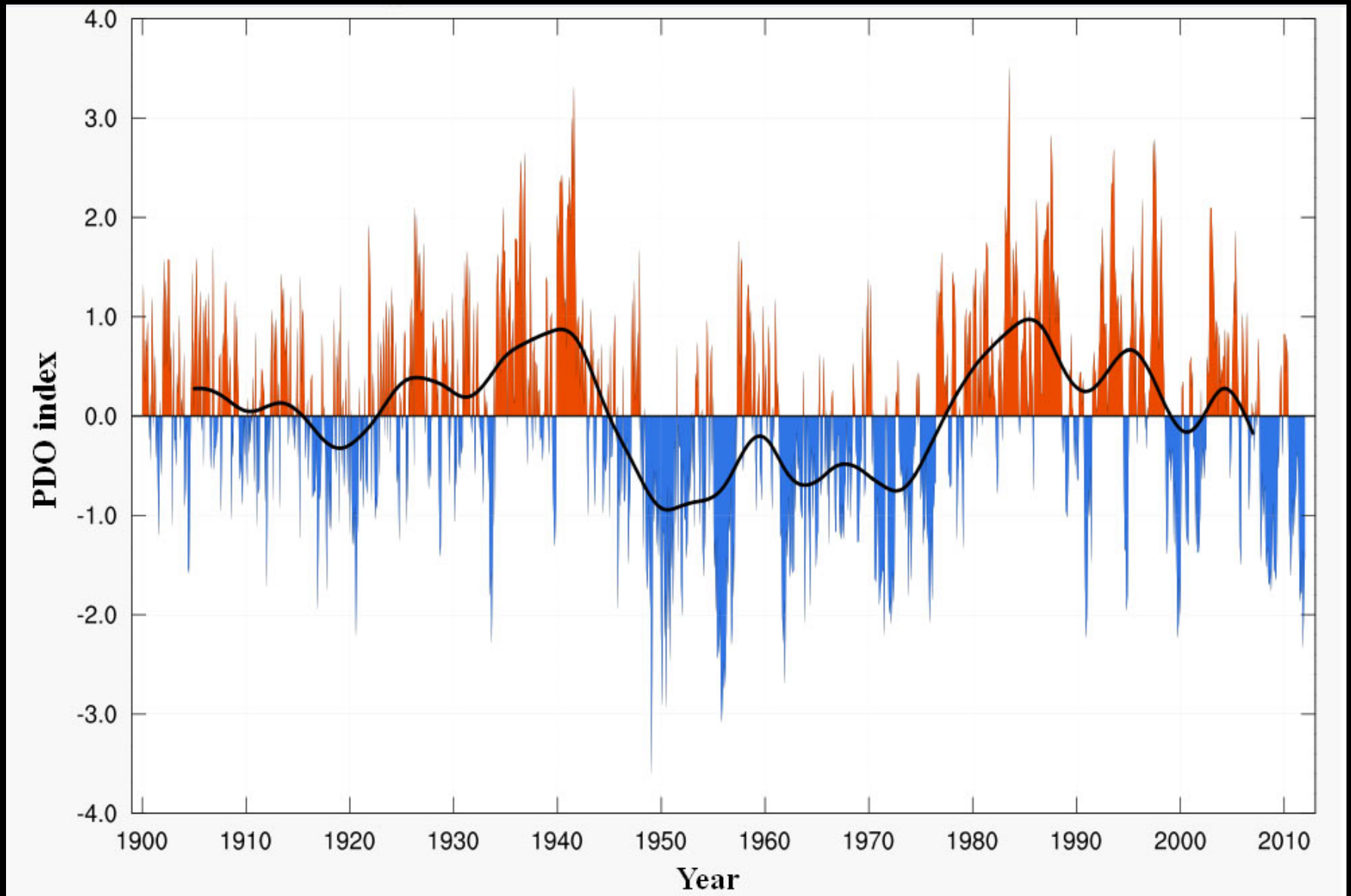
Reason #2: the PDO Cool Phase: Sea Surface Temps Have A Strong Effect on Air Surface Temps

- Recall 93% of the greenhouse heating we have done with our CO2 has been transmitted into the oceans.
- But because the oceans are stratified with less dense warmer water on top, it is difficult and irregular for that hotter water to be conveyed to lower deeper layers, depending on changing global wind patterns
- Hence, the Pacific Decadal and Atlantic Multidecadal Oscillations (PDO, AMO)
- But a SECULAR rise in ocean temps can **only** happen if there is a SOURCE of heat - energy doesn't pop out of nothing, after all! – and that source is our rising **human-generated CO2 Greenhouse insulation**

Most of our atmosphere heating has gone into the top layer of the ocean, less so deeper down. Sea surface temps (SST's) have risen only half of what the air has done – This temp gradient proves that it is HEAT from the ATMOSPHERE that is ultimate heating the ocean, NOT the other way around



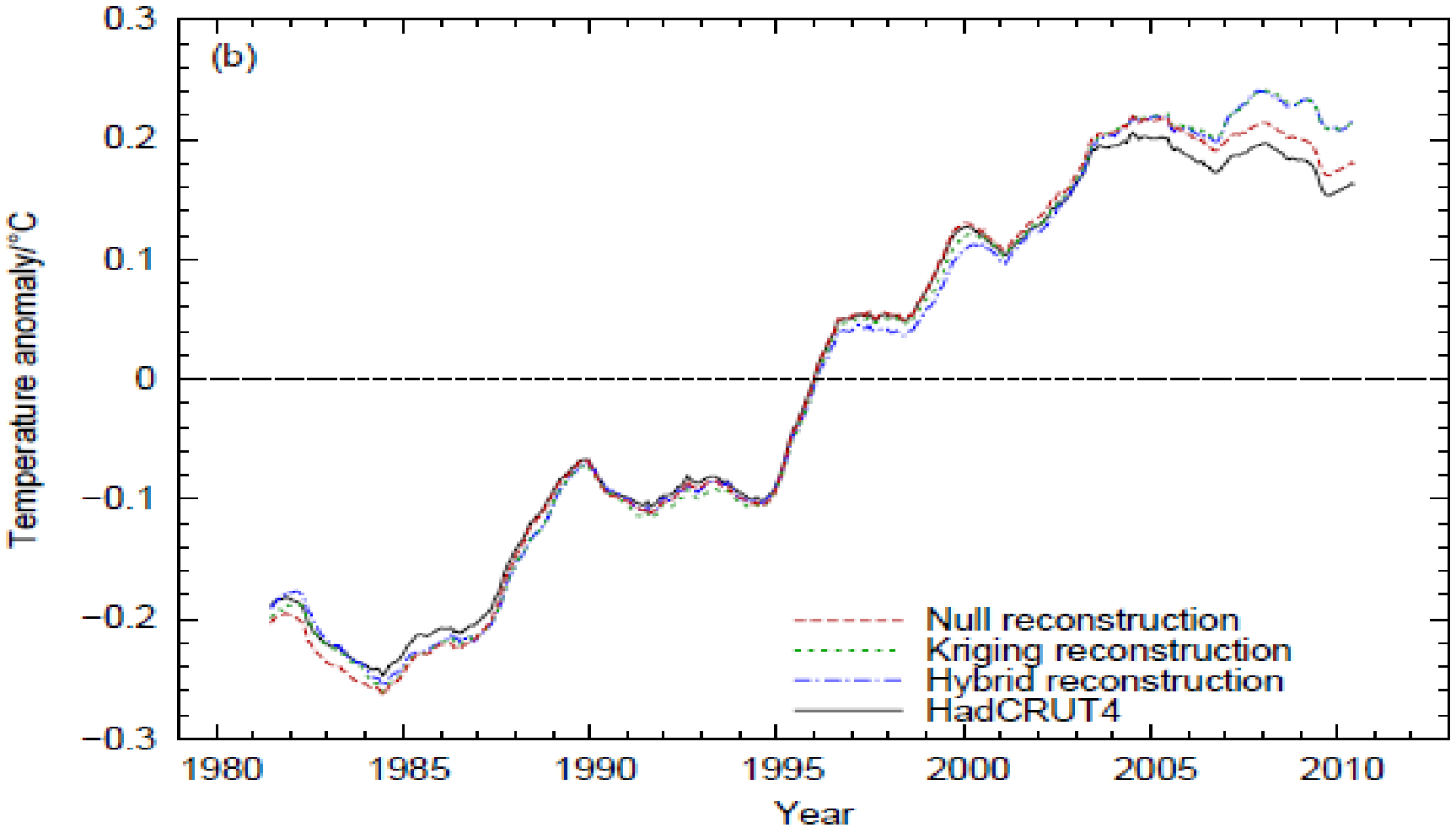
And in 1998-2014 The Pacific Decadal Oscillation was in a Cooling Phase



Reason #3: Missing Arctic Temperatures

- We don't have meteorological stations in the Arctic like we do at lower latitudes.
- The Hadley Center in the U.K., a world leader in climate research, has one of the global temperature datasets and it is predominantly this (**HadCRUT4**) dataset which the climate denialists like to use, because it more than the others, misses the Arctic warming (which is several times more warming than at lower latitudes)
- **Cowtan and Way** (2013) show that when this bias is corrected for, using satellite data for the Arctic, the rise rate in global temps is 0.12C/decade, same as the average since 1950 (but still less than the 1980-1998 period).

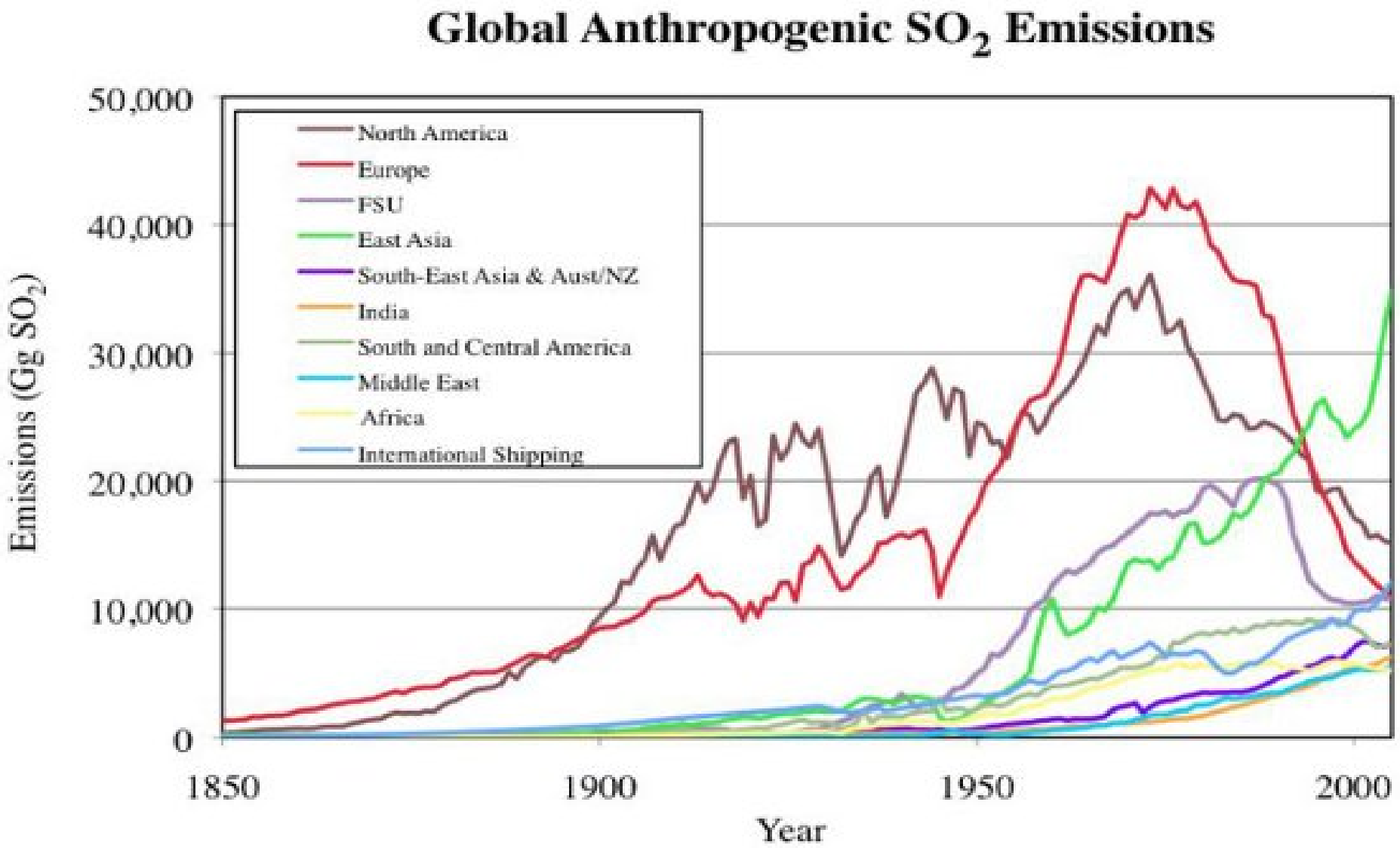
Correcting for missing Arctic temps has the most dramatic effect most recently, since Arctic ice melt is accelerating. Raw temps is the bottom curve, and corrected for missing Arctic temps is the top blue curve



Reason #4: Asian Industrial Air Pollution Now Dominates the World, Overwhelming the Cleaner Air in Europe and North America

- Recall that sulfate air pollution makes a reflective blanket at relatively low altitudes – the "Aerosol Direct Effect", cooling climate just like low clouds.
- These air pollutants also enhance the formation of low clouds themselves – the "Aerosol Indirect Effect", further cooling climate.
- Manktilow (**2009**) (see here) finds that Asian sulfates are even more powerful coolants because local weather patterns loft the aerosols where they remain longer.

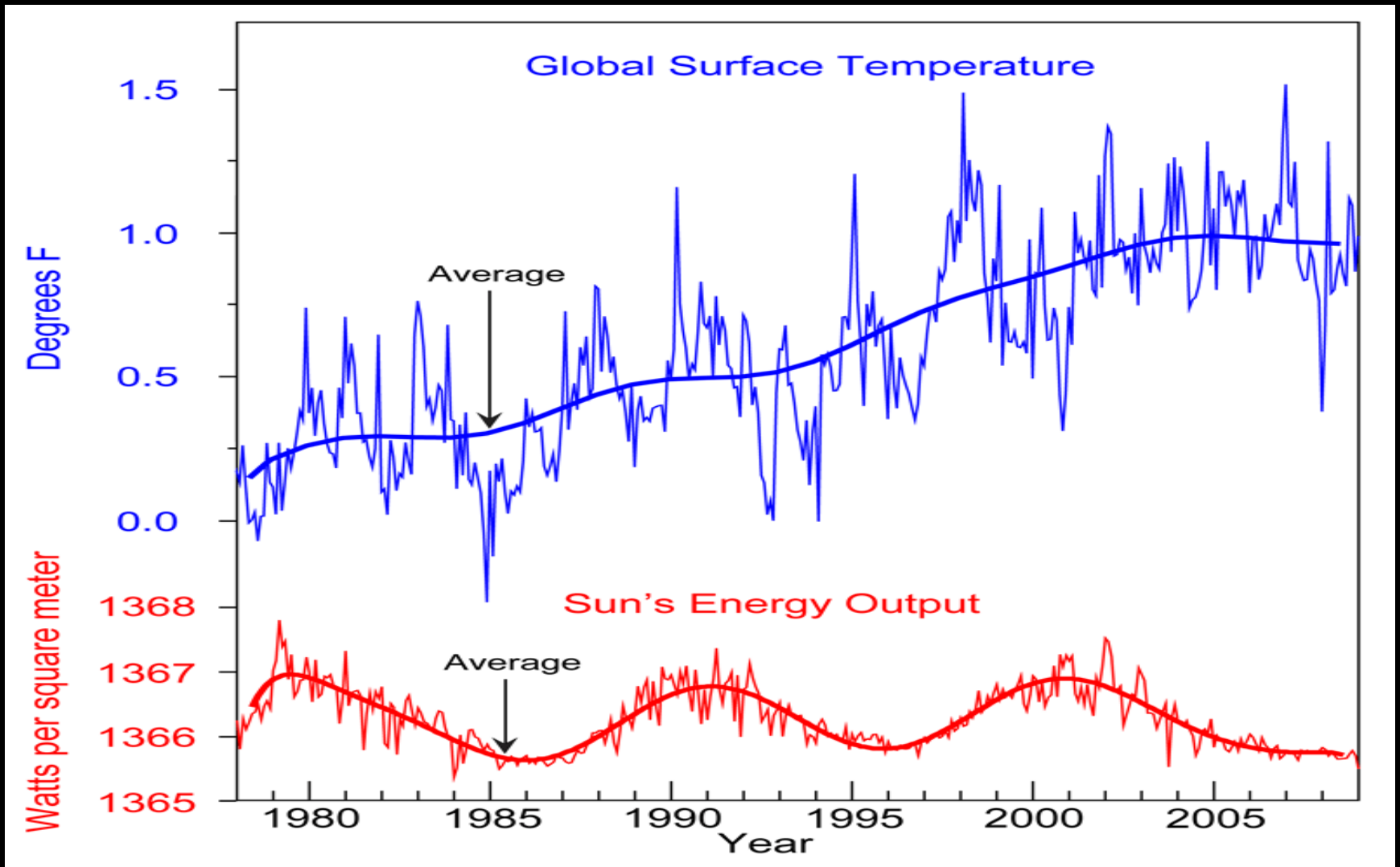
East Asia (green curve, China Mostly) Now Dominates Sulfate Emissions, Cooling Global Climate



Reason #5: Volcanic Aerosols from low-level volcanic activity recently found to be significant, cooling climate

- Santer *et al.* 2014 in the journal *Nature*, find that failure to include early 21st century volcanic aerosols resulted in an overestimate of the temperature trends then.
- It had earlier been assumed that only major volcanic events reaching the stratosphere directly were significant, and there have been few in the 21st century. But including lower-level volcanic aerosols in climate modelling better matches the observations by ~15%.

Reason #6: Solar luminosity forcing has declined; 2007 solar minimum was longest, lowest in a century, and the 2012 solar maximum the weakest in a century



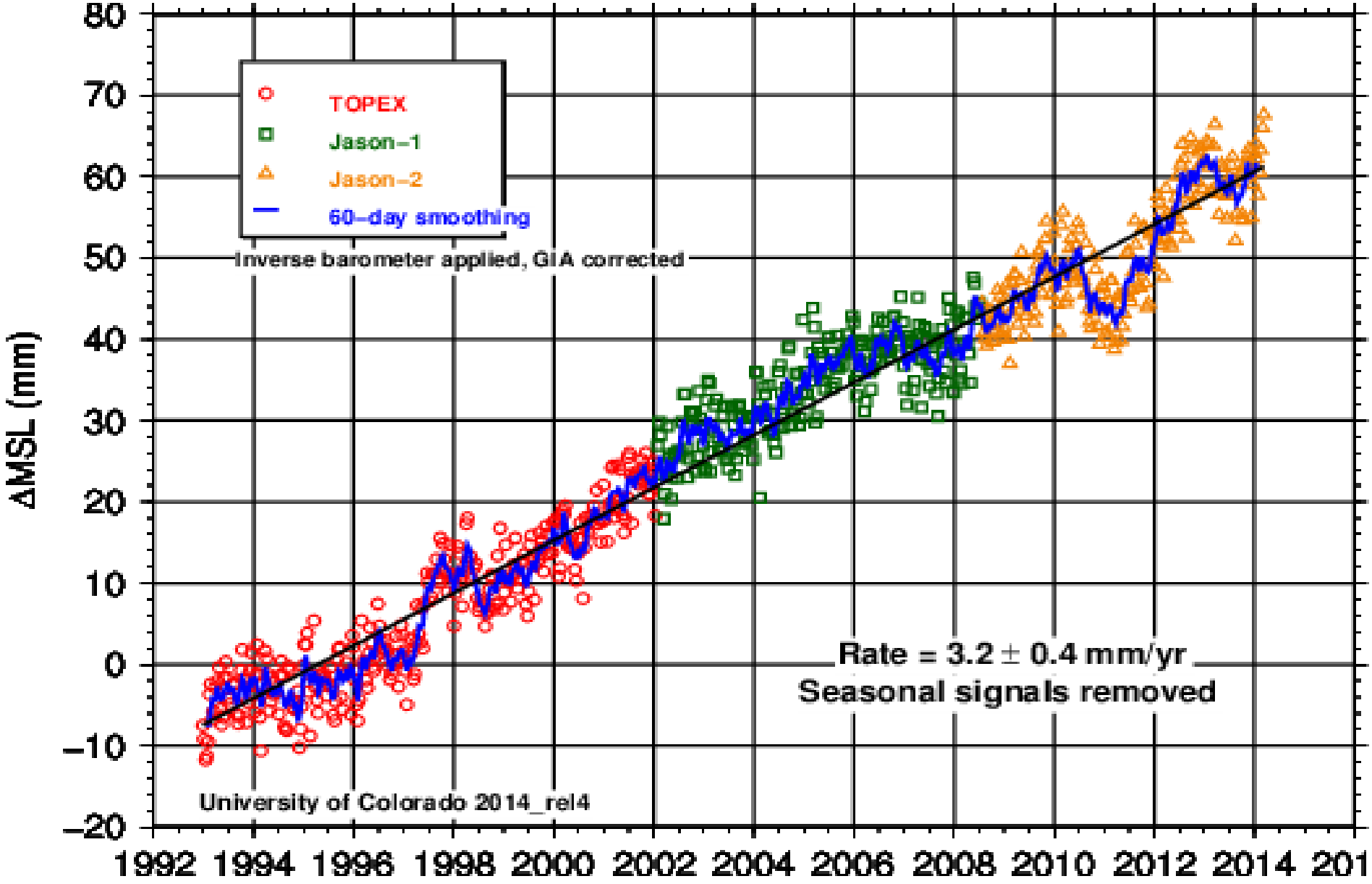
Climate denialists want you to believe that the (faux) "pause" in temperatures proves we don't understand CO2 and climate, and predictions of a dangerous future are nonsense.

- You can't throw rocks at human-caused warming just because we cannot yet predict the irregular cycles of ENSO, PDO, AMO, the exact level of the next solar cycle, and the economic decisions of China.
- In fact, there is no disagreement between our understanding of climate and the temperature trend of the past 17 years when these known (now, after-the-fact) climate forcings are included.
- How can we say this? Consider….

Has Heating of the Earth System Paused at ALL?

- **No.**
- Even with the legitimate reasons above for expecting some cooling included, the accelerating rise in CO2 has compensated and when you look at TOTAL SYSTEM HEATING, we see NO break in trend whatsoever.
- How to do this? One way is: **Global average sea level is an elegant thermometer.** We understand very well the heat needed to expand seawater and to melt ice; the **only** two causes which can raise global average sea levels.
- It's just like the expansion of mercury in your home thermometer.

22 Years of Sea Level Rise – No Pause



Further: Foster and Rahmstorff (2011) Correct 5 Different Temp Datasets for Volcanic aerosols, Solar Luminosity, and ENSO Influences. <u>There is No "Pause"</u>

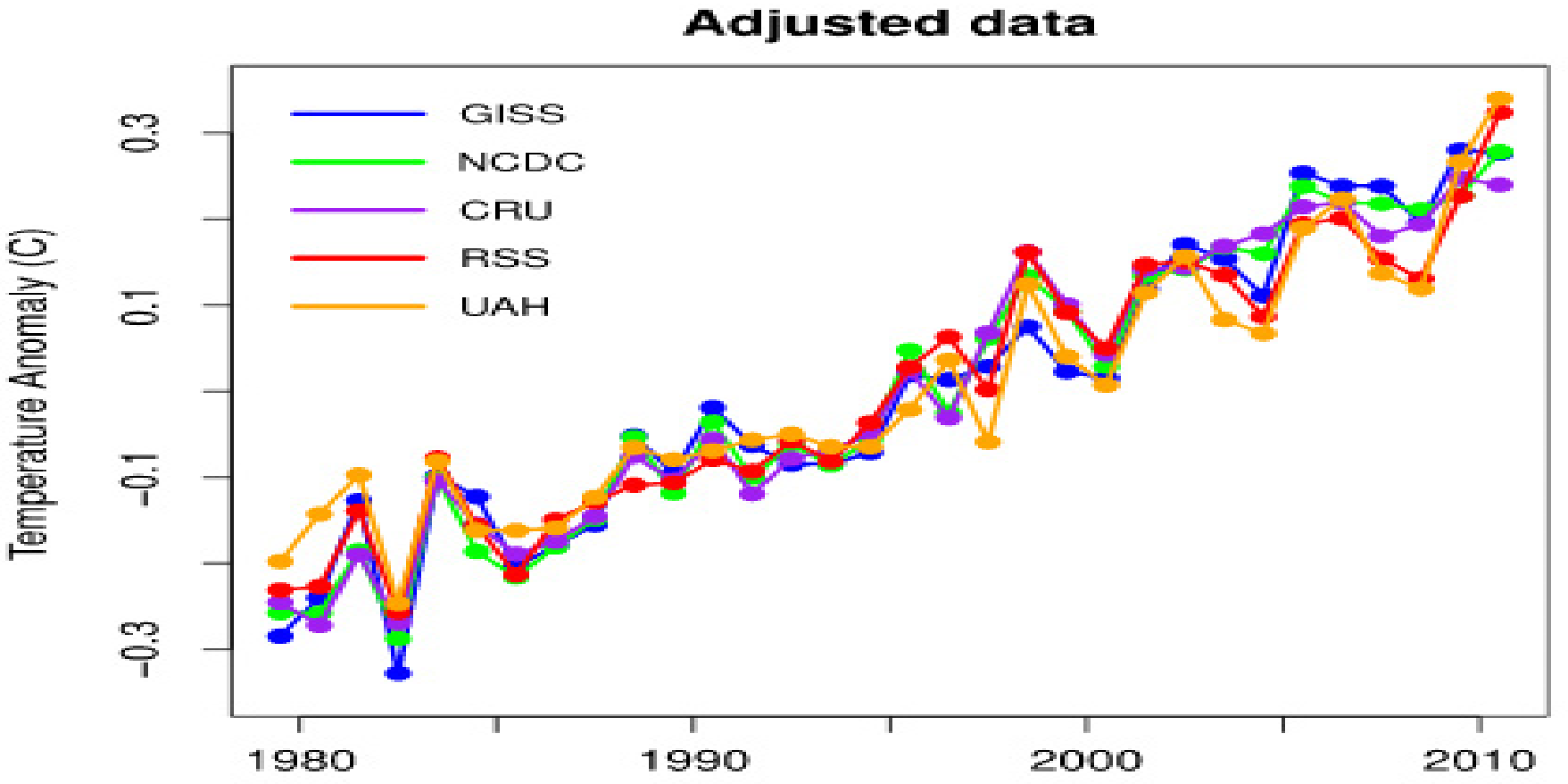
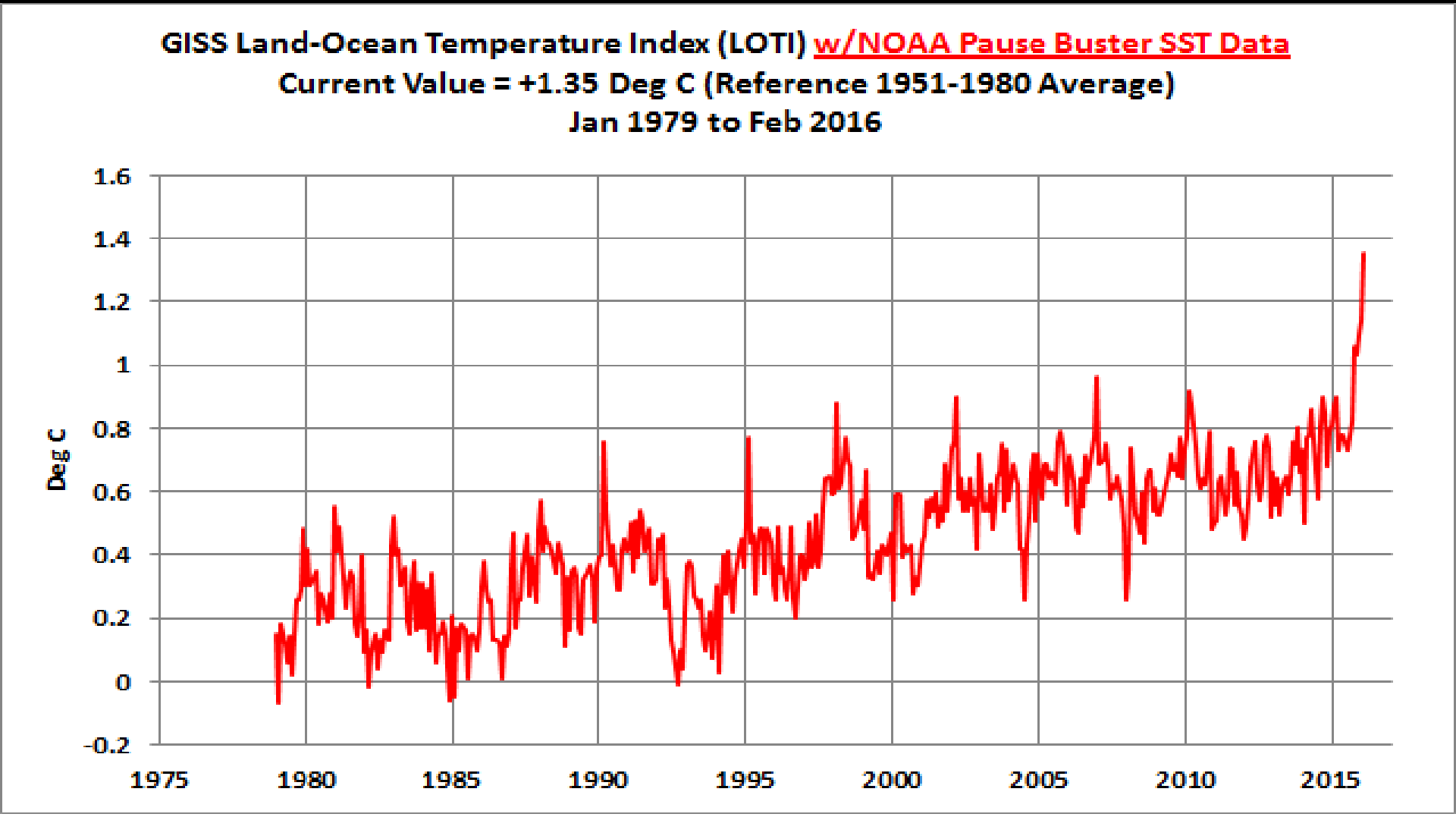


Figure 5. Annual averages of the adjusted data.

We're Entering a 6th Temperature Regime as of 2015

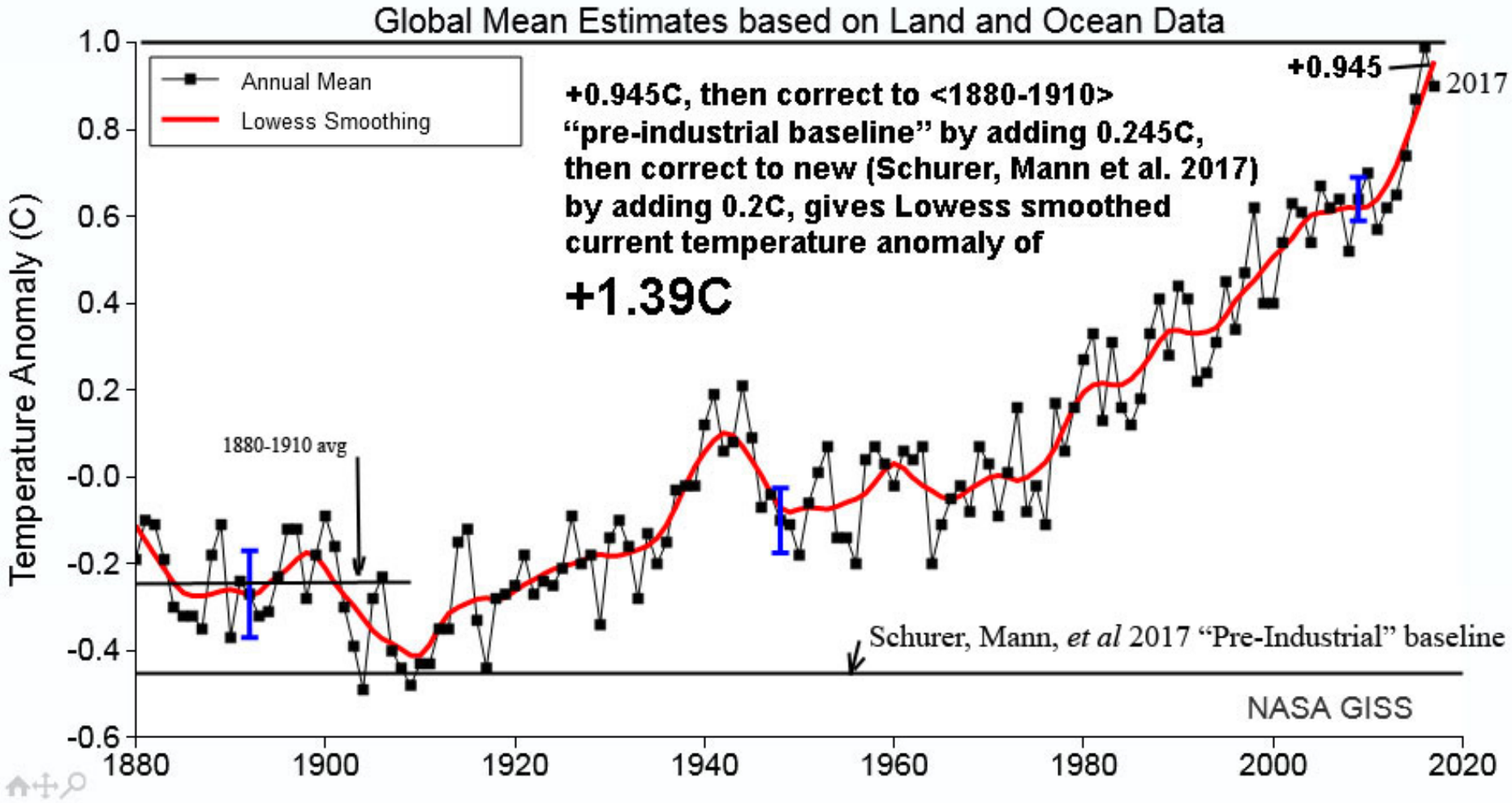
- The PDO cool phase has apparently ended, triggered by the El Nino of 2015, which was as strong or even a bit stronger (for a month), than the record 1997/98 El Nino
- Global temperatures have skyrocketed as the heat built up and covered under the surface of the Pacific piled against Indonesia has spread and flooded back to the surface – El Nino.

NASA GISS Global land-and-sea temps. Now skyrocketing…



Bob Tisdale

Referred to the new Schurer, Mann *et al.* (2017) baseline, shows as of the close of 2017 we were (smoothed red) 1.39C above Pre- Industrial

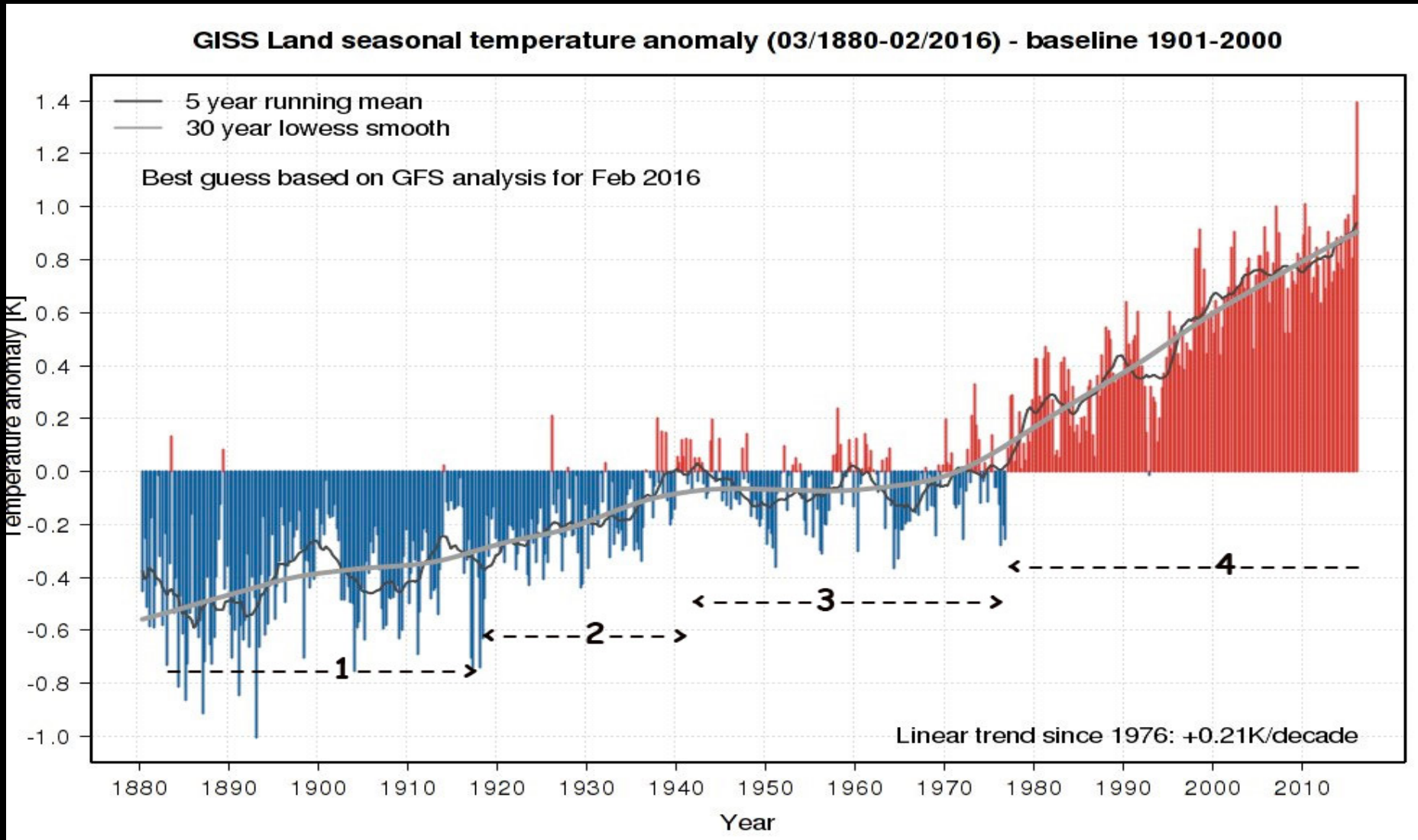


Land-ocean temperature index, 1880 to present, with base period 1951-1980. The solid black line is the global annual mean and the solid red line is the five-year lowess smooth. The blue uncertainty bars (95% confidence limit) account only for incomplete spatial sampling. [This is an update of Fig. 9a in Hansen et al. (2010).]

New Record Temperatures.

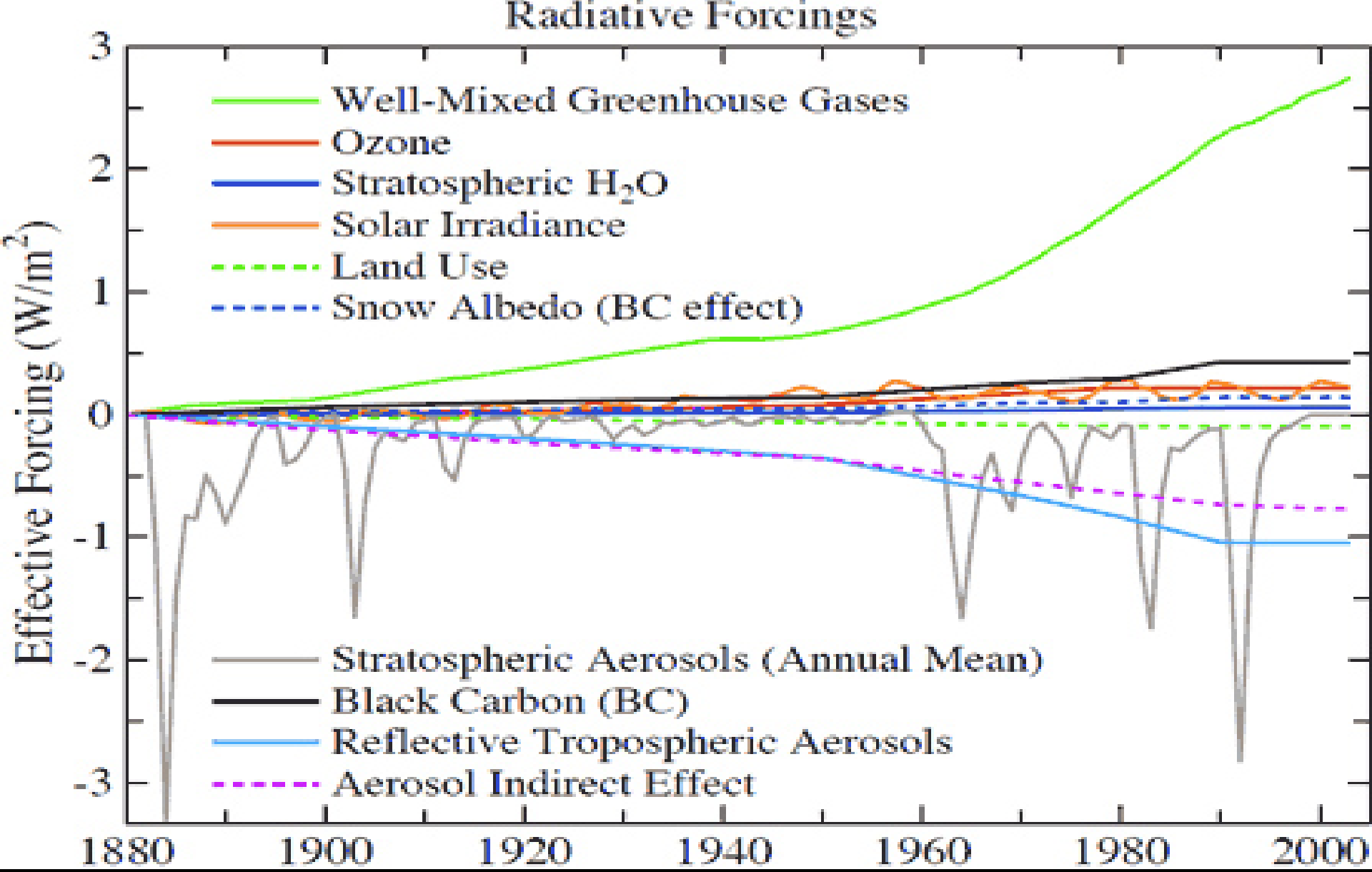
- Temperatures have rejoined and even exceeded the trend set in the 1980-98 period as greenhouse emissions have only accelerated during this period. We're back on trend, and then some.
- However, the 2015 El Nino effect is estimated at only ~20% of the temperature spike we're seeing. Most is GHG's.
- In fact, global extreme temperatures are rising; over 3-sigma faster than would happen in a climate-stable world (**Finkel and Katz 2018**). A significant change in rate happened in 1990 onward.

And in the Longer Context: Still Skyrocketing



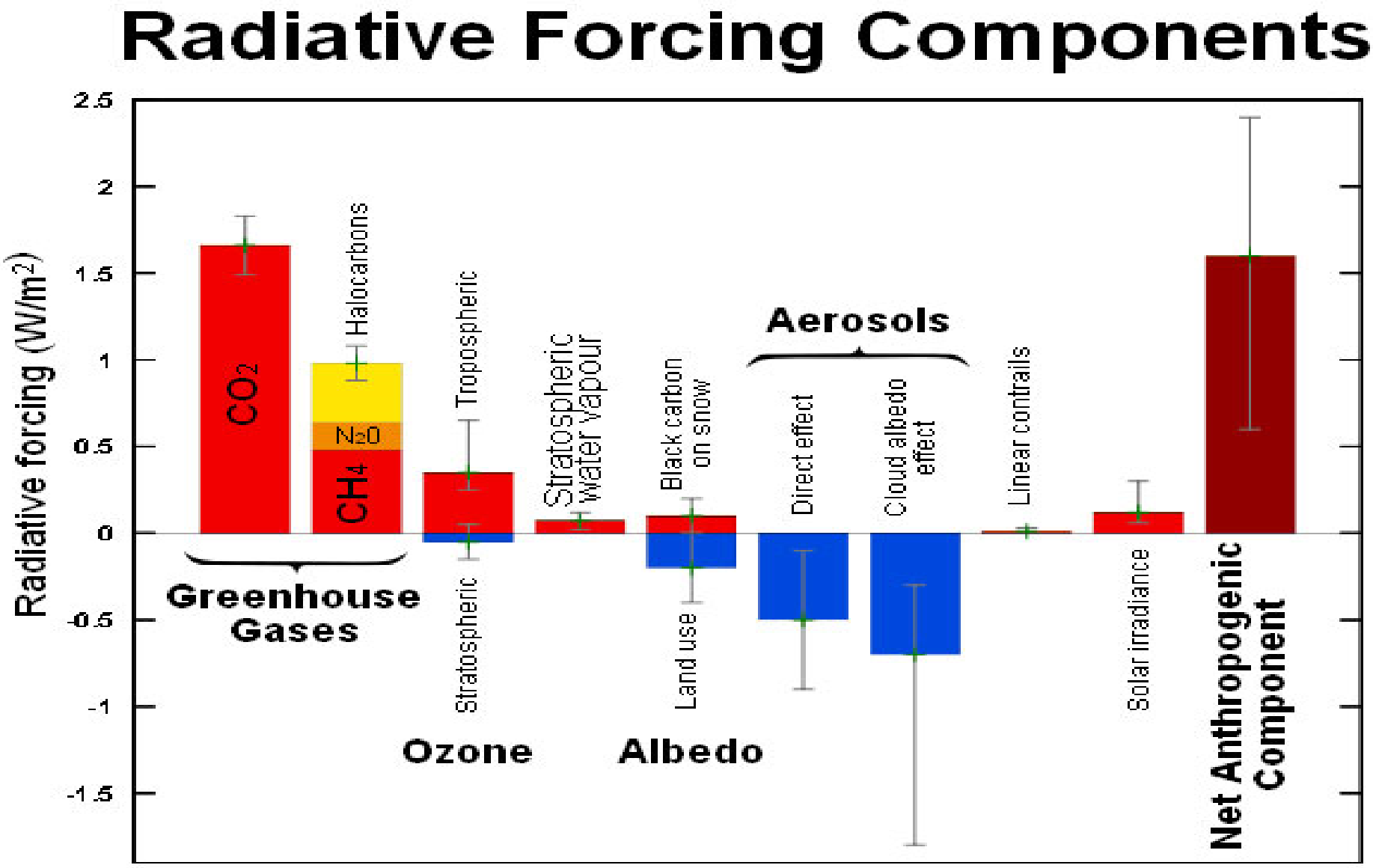
OK - We're done with the 6 periods of modern temperature. Onward…

- 14 sec video – Worldwide temps 1976-2012
- https://www.youtube.com/watch?feature=player_embedded&v=ZAp1o-669xc
- Let's look at the different climate forcings which generate these temperatures



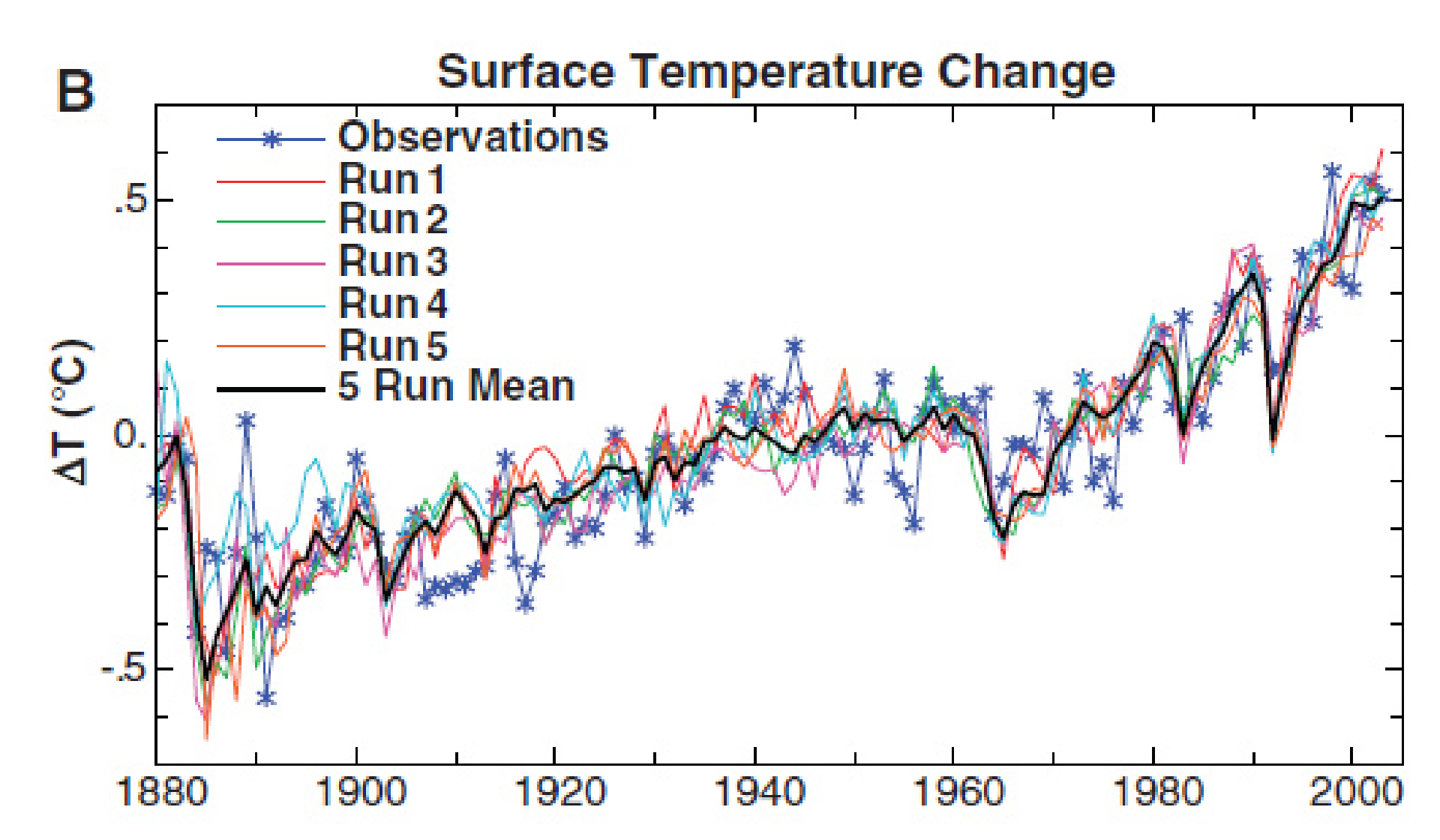
Heating and Cooling Forcings to the Earth's Heat Budget (from Hansen *et.al.* 2005). Forcings calibrated from observations. Combined with the GISS Climate Model, they reproduce observed global temperature in detail very well. See next slide

IPCC AR4 (2007) Climate Forcings: Human and Natural: Averaged from Pre-industrial 1750 to the present. Note how tiny is solar forcing change, even since 1750.



Note that the two biggest climate forcings are both Human-Caused

- **#1 is greenhouse gases**. Primarily CO2, but also some from nitrous oxides and as climate warms, increasing water vapor as well. This forcing **WARMS climate**
- **#2 is reflective (sulfate mostly) aerosols** from human-caused industrial emissions. These both reduce sunlight to the ground, and also increase low cloudiness. Both effects **COOL climate**, but not as much as #1 greenhouse gases WARM climate



Real *vs.* Climate Model Temperatures: (GISS data, from Hansen *et al.* 2005) Before 1900, the observed curve is based on observations at meteorological stations and the model is sampled at the same points, whereas after 1900 the observations include sea surface temperatures for the ocean area, and the model is the true global mean using known aerosol, ENSO forcing (Hansen *et al.* 2001). **Agreement says we are including the relevant physics DURING THIS TIME PERIOD (the future is another story)**

Notes on Climate Forcings from Hansen *et. al.* 2005

*Effective forcings are derived from five-member ensembles of 120-year simulations for each individual forcing and for all forcings acting at once [see (9) and supporting online material]. The sum of individual forcings differs slightly from all forcings acting at once because of nonlinearities in combined forcings and unforced variability in climate simulations.

* This is the ozone forcing in our principal IPCC simulations; it decreases from 0.24 to 0.22 W/m^2 when the stratospheric ozone change of Randel and Wu (S1) is used

* Ozone and black carbon forcings are less than they would be for conventional forcing definitions (11), because their ‘‘efficacy’’ is only 75% (9)

Methane *vs.* CO2

- Averaged over the ~250 yr Industrial Age, **methane provided about ¼ of the heat forcing that CO2 does** (there is MUCH less methane in the atmosphere than CO2)
- This has been changing rapidly, both from expanding livestock, and recently as Arctic methane trapped in the permafrost is liberated as the Arctic Ocean permanent ice disappears and the albedo effect causes more dramatic warming of the Arctic.
- More on Arctic and tropical methane emissions and reservoirs later

Key Points: K38a Current Climate- Temperatures

- Past 2000 years till Fossil Fuel Era; very slight, slow, cooling by astronomical (Milankovitch) forcing.
- “Medieval Warm Period” very slight, mostly European data, fewer volcanics, higher solar luminosity.
- “Little Ice Age”: continuation of Milankovic cooling, higher volcanics, Columbian and Black Plague led to reforestation, uptake of CO2.
- To 1912: slight cooling due to enhanced volcanic aerosols. Human effects minimal
- 1912-1945: Rising temps due to fossil fuels, solar activity, pause in volcanic aerosols
- 1945~1975: Flat temps as rising CO2 heating offset by cooling aerosol pollution, helped a bit by low phase of Pacific temps
- Since ~1975: Accelerating fossil fuel burning now dominates all other forcings, including cooling due to solar activity, flat to dropping PDO. Also, Clean Air Act reduces aerosol cooling until Asia industrializes
- Apparent “Pause” in global average surface temperatures disappears when missing Arctic temperatures, low solar L, rising Asian sulfate aerosols, and ocean oscillations are included.
- Avg’d since 1750, CO2 dominates, methane ¼ as much. Human activities dominate over all other forcings, and human heating (CO2) dominates over air pollution aerosol cooling
- Temperatures today are higher than any time in human history, skyrocketing after 2015 El Nino