Forecasting Global Temperatures by Exploiting Cointegration with Radiative Forcing

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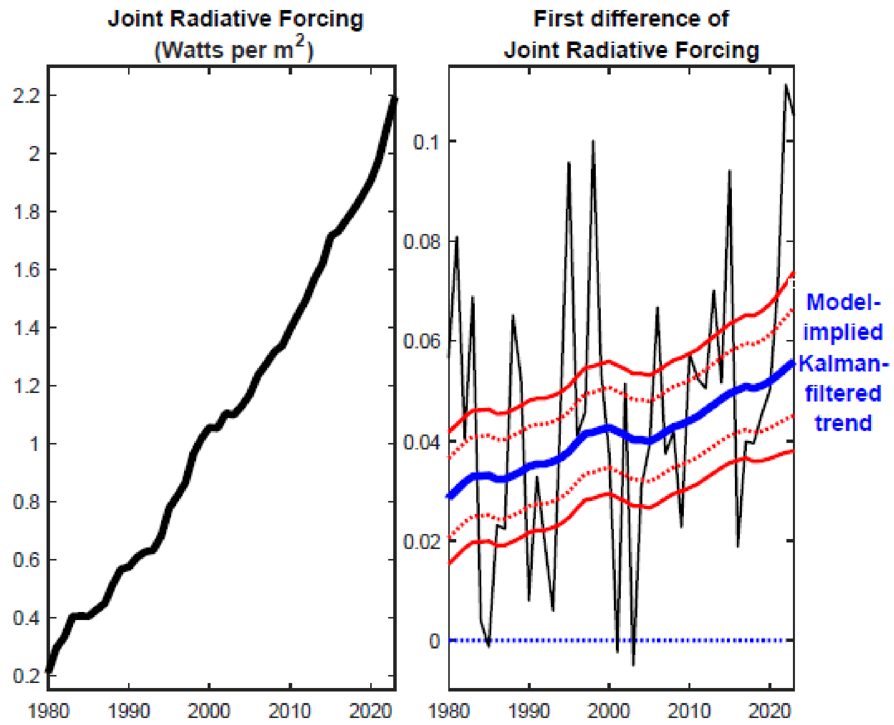
April 18, 2024

This paper: Brief overview

Use VARs to forecast global temperatures by exploiting their cointegration with Joint Radiative Forcing (JRF) of 7 drivers of climate change (CO2, methane, CFCs, SOx …) …

Radiative Forcing—in Watts/m^2—measures ability of climate change drivers to trap heat …

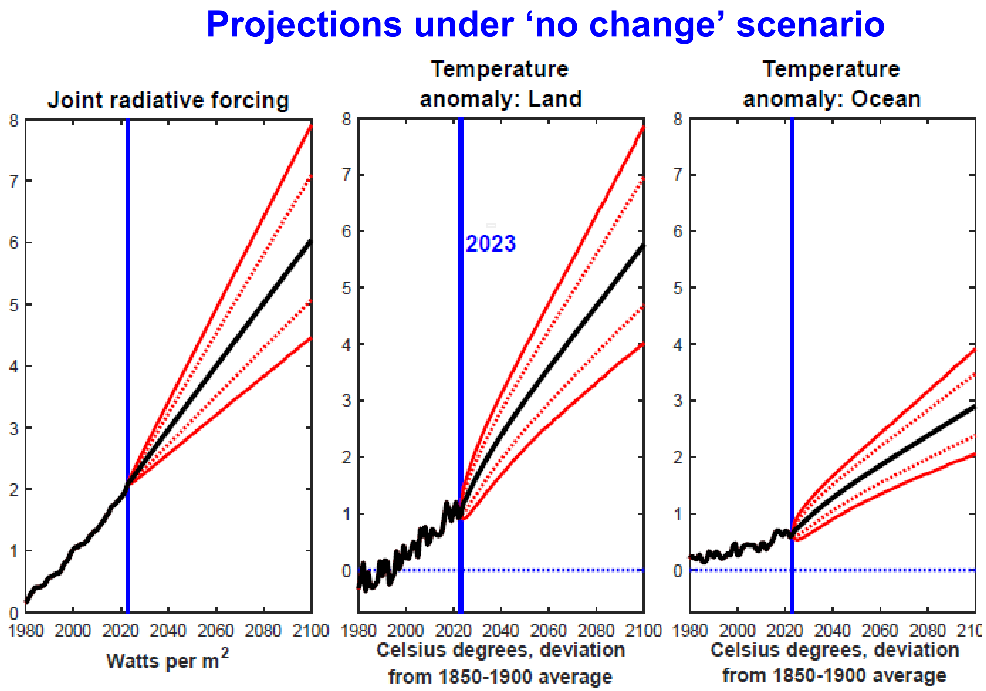


Main results:

(I) Increase in JRF has markedly <u>accelerated</u> since end of 1970s (see right hand-side panel) …

When considering all drivers of climate change, no evidence of an improvement: problem is steadily <u>getting worse</u> …

2022 and 2023 associated with <u>largest increases</u> in JRF ever …



(II) Under 'no change' scenario, median forecasts project global land and ocean temperature anomalies to reach nearly 6 and 3 Celsius degrees in 2100 (see left) …

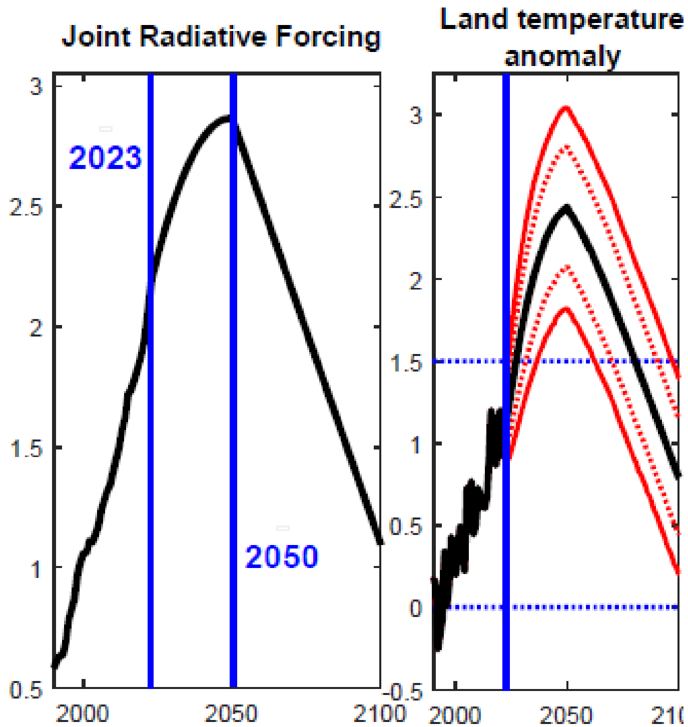
For Europe, projected increase between 2023 and 2100—about 6 Celsius degrees—is close to forecasts of European Environment Agency's *Copernicus* …

<u>Some perspective</u>: lower bound of estimates for temperature increase associated with Paleocene-Eocene Thermal Maximum (PETM), 55.5 million years ago, is 5 Celsius degrees …

Around PETM, Antarctica featured tropical forests, and alligators roamed northern Canada …

Crucial point Carbon increase that caused PETM lasted between 20,000 and 50,000 years, not about 200 years …

'Experiment' we have embarked upon since Industrial Revolution is unprecedented in Earth's history …



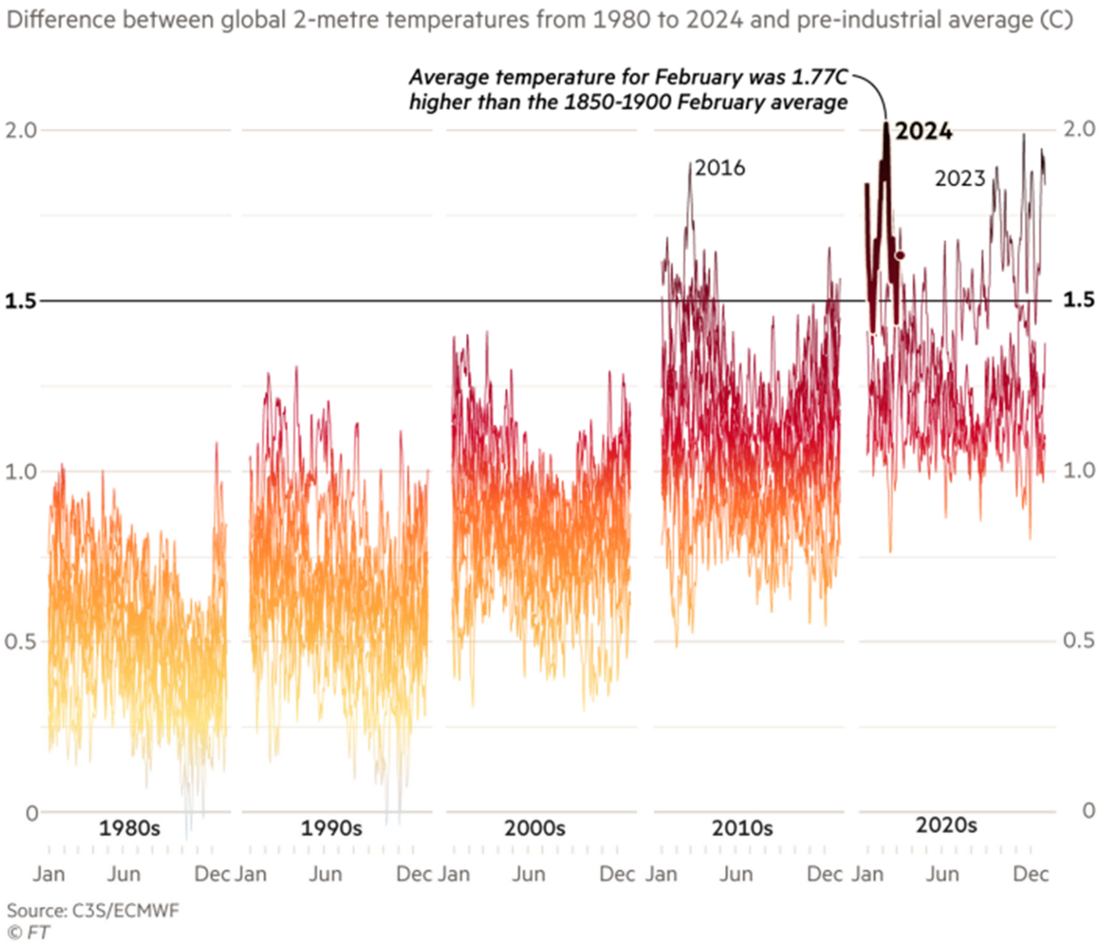
(III) Forecasts conditional on alternative JRF paths suggest bringing climate change under control will require driving JRF back to levels of early XXI century …

Outline of today's talk

- **Motivation**
- **Dataset**
- **Evidence from statistical tests**
- **Modelling framework**
- **Evidence on acceleration of anthropogenic climate change since end of 1970s**
- **Evidence from forecasts**
  (*i*) under 'no change' scenario, and
  (*ii*) conditional on alternative JRF paths
- **Some final thoughts**

Motivation

Marked <u>acceleration</u> of climate change in recent years …



Large amount of evidence on this: will show two especially stark pieces …

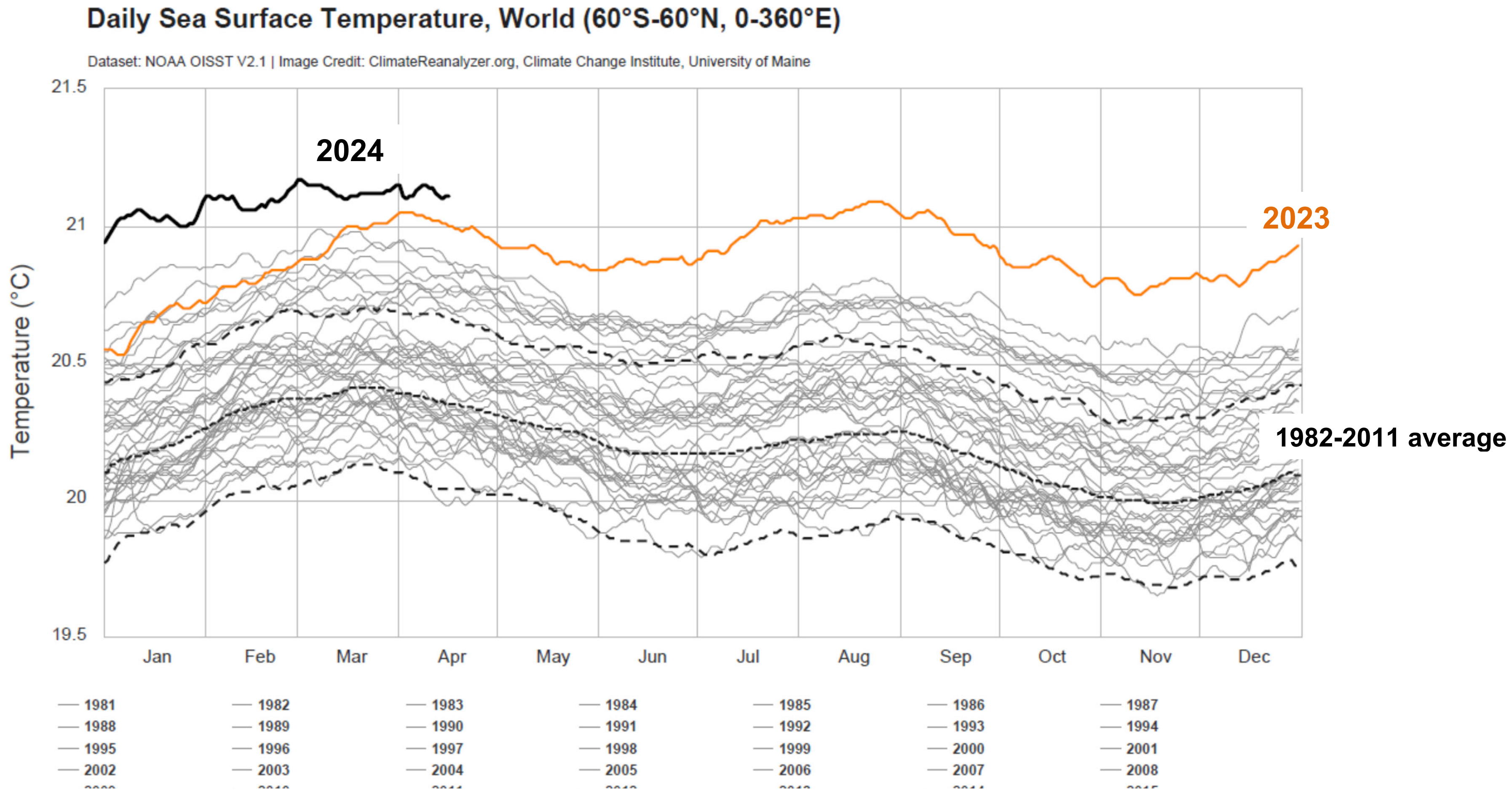
Left: monthly temperatures by decade …

Two things stand out:

(1) marked <u>increase since 1970s</u>, and

(2) <u>2023 and 2024</u> appear as <u>out of kilter</u> with previous observations …

This is especially apparent when focusing on <u>oceans</u>' temperatures (next slide) …



Why? Oceans act as a <u>low-pass filter</u> for temperatures' fluctuations … Historically, changes in ocean's temperatures have consistently been <u>very slow</u>: 2023 therefore came as a shock to climate scientists …

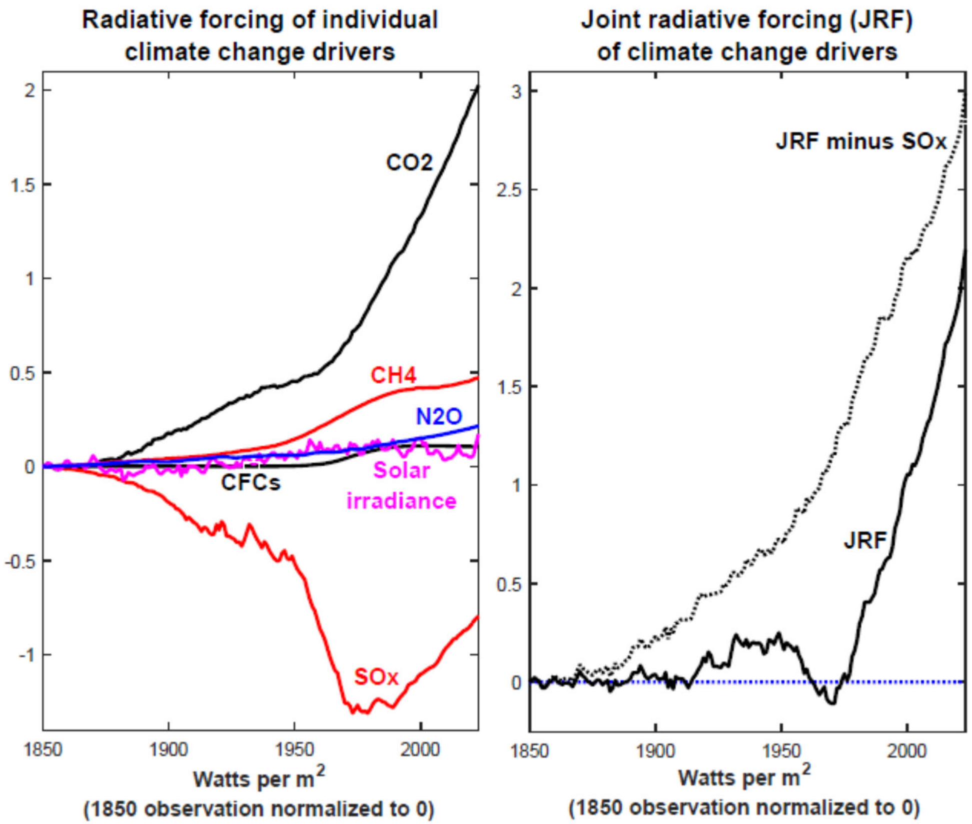
In a March 21, 2024 article in *Nature*, Gavin Schmidt, director of NASA's Goddard Institute, stated that

'… no year has confounded climate scientists' predictive capabilities more than 2023 has. For the past nine months, mean land and sea surface temperatures have overshot previous records each month by up to 0.2 °C—a huge margin at the planetary scale.'

'If the anomaly does not stabilize by August, then the world will be in uncharted territory.'

On this, more later …

The dataset



Following (e.g.) Kaufmann, Kauppi, and Stock (*Climate Change*, 2006) I consider 7 drivers of climate change, which I convert into Radiative Forcing (RF) based on standard formulas found (e.g.) in IPCC reports …

JRF index computed as sum of individual RFs …

Since 1950s, 3 main drivers of JRF: CO2, methane (CH4), and anthropogenic sulfur emissions (SOx) …

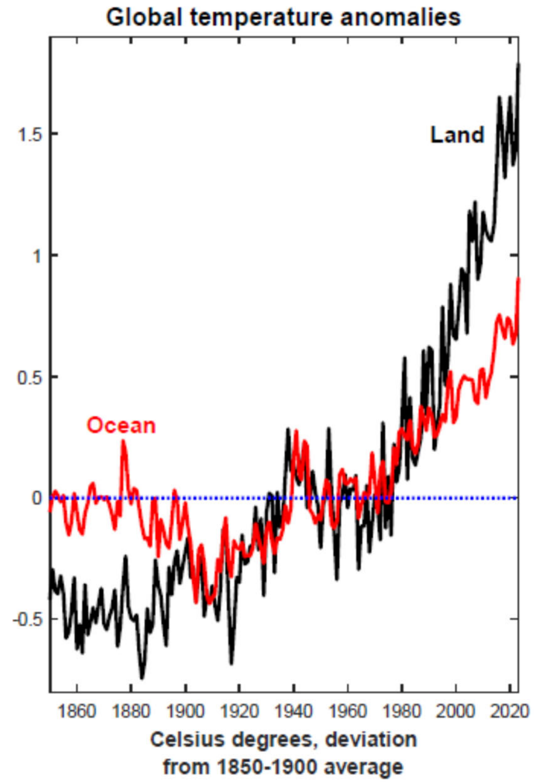
Until about 1980, increase in SOx pollution slowed down JRF: since then, cleaning-up of atmosphere contributed to increase in JRF …

Sample period is 1850-2023 …

Consider temperature anomalies for both land and ocean …

<u>Rationale</u>: since 1850 ocean has warmed significantly more slowly than land (see right) …

Focusing on global average (i.e., land and ocean) would hide this, and present distorted picture: ultimately, what is most relevant for humans is land temperature …



Data sources are standard: e.g., for temperature anomalies the U.S. National Oceanic and Atmospheric Administration (NOAA) …

Evidence from statistical tests

Elliot, Rothenberg, and Stock's (*Econometrica*, 1996) tests

- **cannot reject unit root in levels of JRF and temperature anomalies' series, but**
- **typically reject unit root for series' first differences …**

In line with majority of previous studies, this suggests series are I(1) …

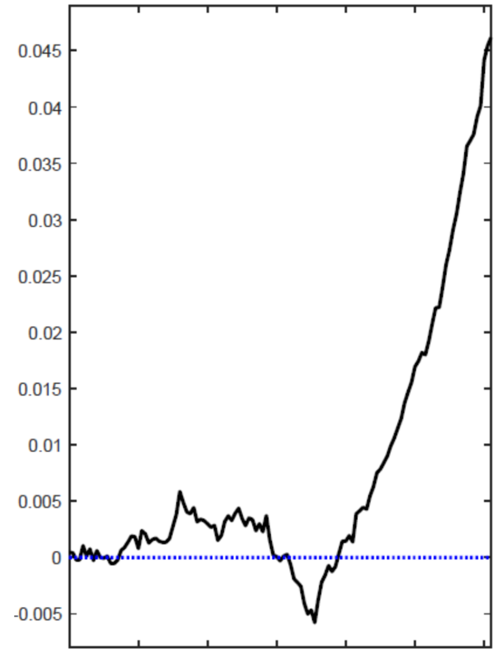
However, <u>first</u>: first differences of series clearly exhibit non-negligible low-frequency variation …

Right: 50-year rolling average of first difference of JRF …

Evidence for temperature series qualitatively the same …

Compatible with presence of small I(1) component in first differences of series …

50-years rolling average of first difference of JRF



Crucially, <u>second</u>: Stock and Watson's (*JBES*, 1996; *JASA*, 1998) tests reject null of time-invariance in means of first differences against alternative of random-walk time-variation …

Table 2 Simulated p-values for Stock and Watson's tests for the null of time-invariance against the alternative of random-walk time-variation in the mean of the first differences of the series

	JRF index[a]			Temperature anomalies	
HAC correction:	Mean	Median	Fraction below 10%	Land	Ocean
	Trimming: 0.15				
Newey and West (1987)	0.0448	0.0148	0.8590	0.000	0.049
Andrews (1991)	0.0531	0.0209	0.8590	0.000	0.112
	Trimming: 0.25				
Newey and West (1987)	0.0409	0.0120	0.8480	0.001	0.041
Andrews (1991)	0.0480	0.0171	0.8480	0.000	0.088
	Trimming: 0.33				
Newey and West (1987)	0.0754	0.0488	0.7740	0.003	0.044
Andrews (1991)	0.0864	0.0591	0.7700	0.001	0.094

[a] Mean and median of the Monte Carlo distribution of p-values, and fraction of p-values smaller than 10%.

<u>Natural interpretation</u>: means of first differences of series feature small <u>random-walk component</u>, due to progressive acceleration of JRF, driven by CO2, CH4, SOx …

In principle, <u>alternative interpretation</u> could be that DGP is fixed-coefficients cointegrated I(2) VAR (will show that in fact series are cointegrated): However, <u>Monte Carlo</u> evidence clearly shows this is <u>not</u> the case …

Modelling framework

In line with previous literature, will show JRF and temperature anomalies are <u>cointegrated</u> …

Let standard cointegrated VECM representation for vector of I(1) series Y_t be

$$\Delta Y_t = B_0 + B_1 \Delta Y_{t-1} + ... + B_p \Delta Y_{t-p} + \alpha\beta' Y_{t-1} + u_t$$

where β is matrix of cointegration vectors and α is matrix of loading coefficients …

Let M be time-invariant unconditional mean of ΔY_t, with

$$B_0 = [I_N - B_1 - ... - B_p]M$$

Then, expression above can be rewritten as

$$\Delta Y_t - M = B_1(\Delta Y_{t-1} - M) + ... + B_p(\Delta Y_{t-p} - M) + \alpha\beta' Y_{t-1} + u_t$$

This I(1) cointegrated VAR model would be appropriate <u>if</u> first differences of series did <u>not</u> feature RW time-variation …

However, we saw Stock-Watson tests do suggest they feature RW time-variation in the mean …

Natural way of modelling this: mean M follows multivariate random walk specification, subject to restrictions imposed by cointegration between levels of series …

Let Y_t be:

$$Y_t = [JRF_t,\ T_t^{\text{Land}},\ T_t^{\text{Ocean}}]'$$

Since both temperature anomalies are cointegrated with JRF, system features an I(2) stochastic trend, and 2 cointegration vectors …

Natural rotation of cointegration space is obtained by defining matrix of cointegration vectors as

$$\beta = \begin{bmatrix} 1 & 1 \\ -b_{\text{Land}} & 0 \\ 0 & -b_{\text{Ocean}} \end{bmatrix}$$

Finally, expression for β imposes following restriction on time-varying mean M_t:

$$M_t = \begin{bmatrix} 1 \\ \frac{1}{b_{\text{Land}}} \\ \frac{1}{b_{\text{Ocean}}} \end{bmatrix} \mu_t$$

$$\mu_t = \mu_{t-1} + \epsilon_{\mu,t}$$

Scalar random-walk μ_t captures common stochastic trend driving frequency-zero dynamics of ΔY_t, i.e. anthropogenic climate change …

Model implies JRF and temperature anomalies maintain long-run equilibrium relationship in response to permanent shocks to both level of JRF, and its first difference …

Estimation

Model estimated via MLE, subject to restrictions on normalized impulse-response functions (IRFs) to permanent shock to JRF …

Each IRF is normalized by its corresponding long-run impact …

Restrictions: at all horizons

- **response of ocean temperature anomaly is slower than response of land temperature anomaly …**

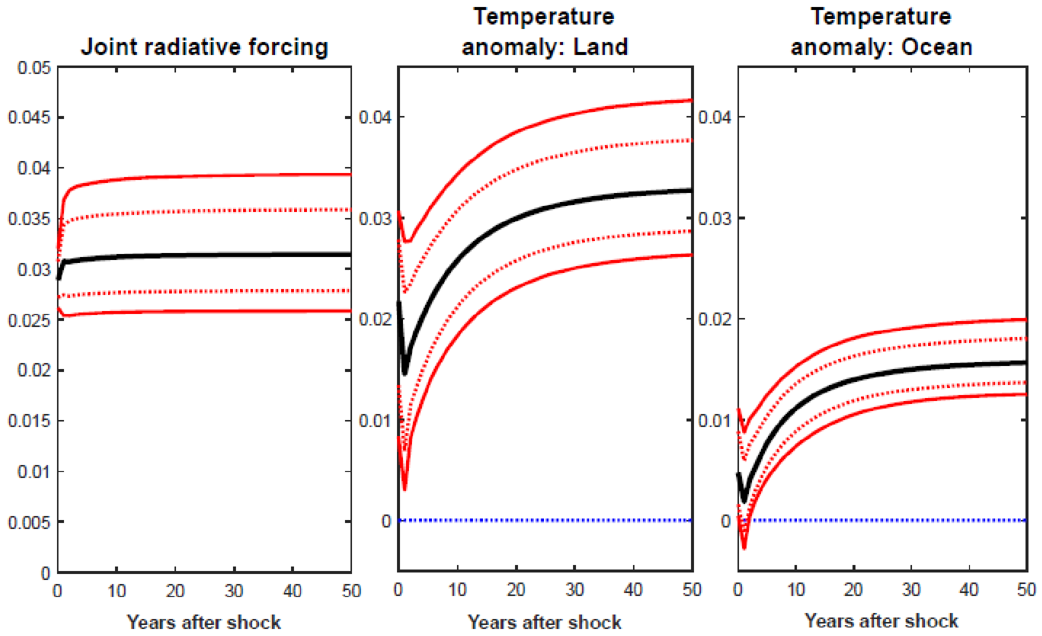
  I.e., normalized IRF of ocean anomaly is uniformly below normalized IRF of land anomaly …

  Restriction reflects slower warming of oceans in response to increases in JRF compared to land (slide 9) …
- **Response of land anomaly is slower than response of JRF …**

  Matter of simple logic: following permanent JRF shock, land anomaly cannot react faster than JRF itself …

Stochastically map constrained log-likelihood's hypersurface via Random-Walk Metropolis …

I: Impulse-response functions to permanent JRF shock



JRF exhibits typical IRF of pure unit root processes …

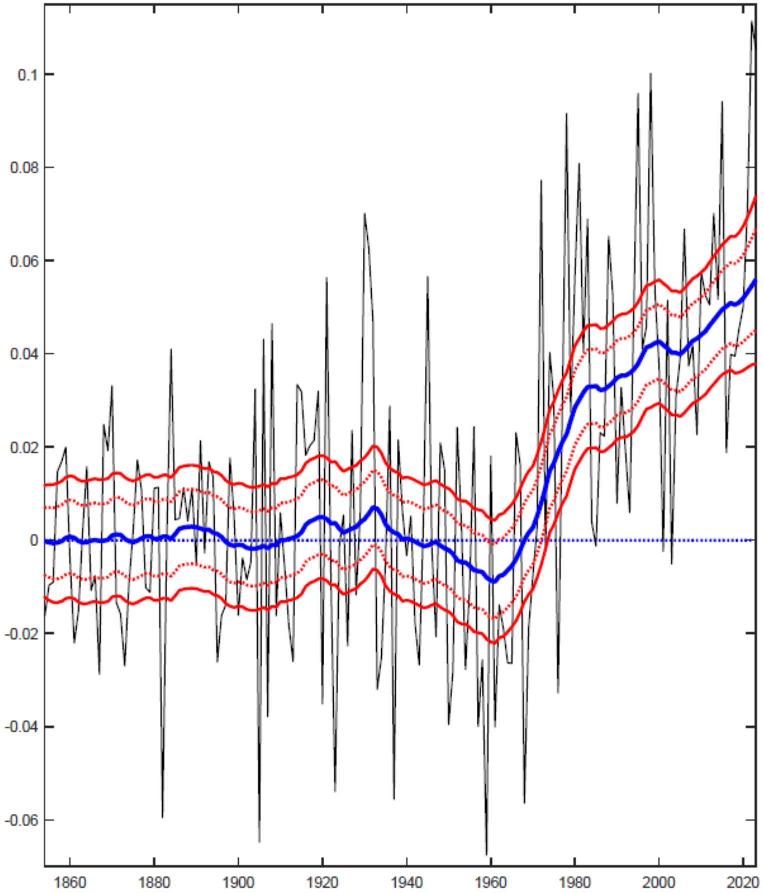
IRFs for land and ocean suggest instead they reach new long-run equilibrium at least 50 years after shock …

However, consistent with recent evidence from climate science literature—see e.g. discussion in Michael Mann's (2023) book—the bulk of the impact takes place within about 20 years …

Implication: The scorching temperatures of 2022-2023 had been largely determined in the early XXI century …

The dramatic increases in JRF since then portend even worse outcomes around the mid-XXI century …

II: Evidence on recent acceleration of increase in JRF



First difference of JRF, and two-sided estimate of μ_t

Left: first difference of JRF, and two-sided estimate of μ_t …

1940s to 1960s: decrease due to explosion in anthropogenic sulfur emissions …

Since 1970s, progressive increase …

No evidence of decrease in recent years: rather, most recent period characterized by fastest increase in JRF ever …

Even focusing uniquely on dynamics of JRF—disregarding e.g. recent crossing of multiple 'tipping points' in Earth system (see 2023 article in *Nature*)—climate crisis is getting progressively worse …

III: Evidence on cointegration between JRF and temperature anomalies

Previous literature, assuming climate change series are either I(1) or I(2), has uniformly suggested that they are cointegrated …

I obtain same result …

Based on climate science literature, relevant null hypothesis is level of JRF is cointegrated with level of either temperature anomaly, so that even if all series are I(2), residual from cointegrating regression

$$T_t = a + bJRF_t + u_t$$

—where T_t is either temperature anomaly—is I(0) …

I test for null of cointegration between JRF and T_t based on Wright's (*JBES*, 2000) test as follows:

- **I perform Wright test for null hypothesis of cointegration between JRF and T_t …**

- **I simulate estimated cointegrated VAR with RW time-variation in mean of first differences: this produces artificial paths for the 3 series …**
- **For each simulation, compute test statistic for either regression based on simulated data: this builds up Monte Carlo distribution of test statistic under null hypothesis that**
  (*i*) all series are I(2),
  (*ii*) they are cointegrated, and
  (*iii*) cointegration residual in regression

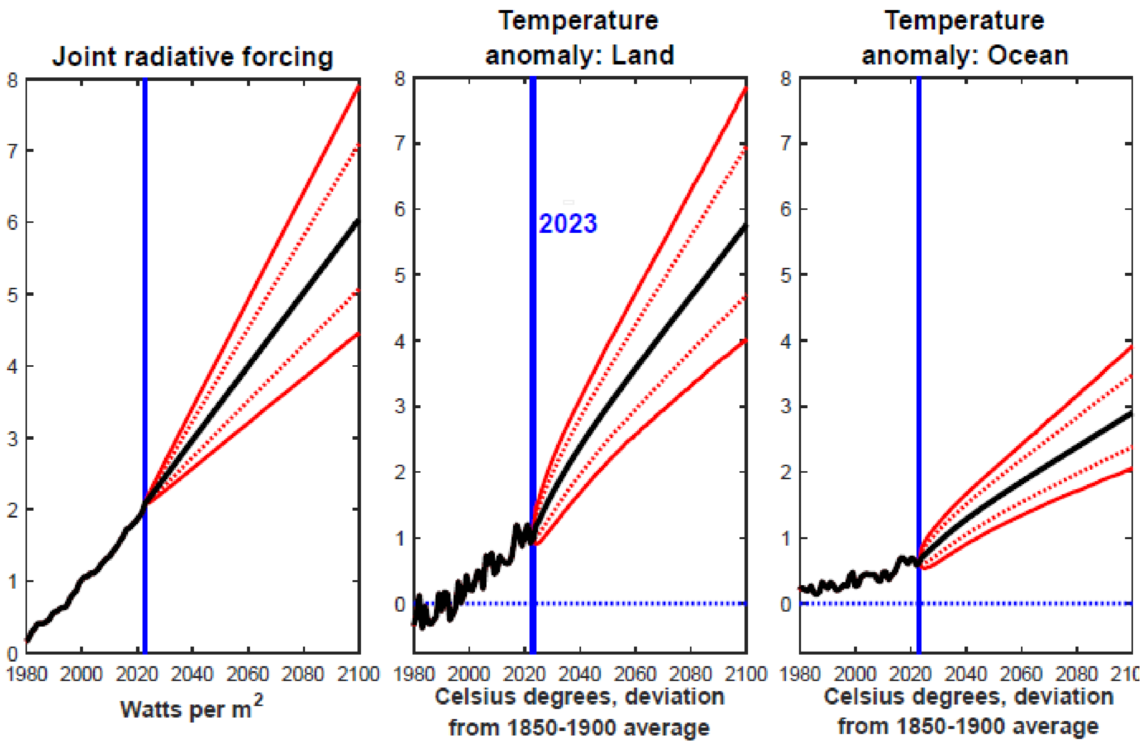
$$T_t = a + bJRF_t + u_t$$

  is I(0) …

Null of <u>cointegration cannot be rejected</u> for either anomaly …

IV: Forecasts under ‘no change’ scenario

For each draw from distribution of constrained log-likelihood produced by Random-Walk Metropolis I proceed as follows …

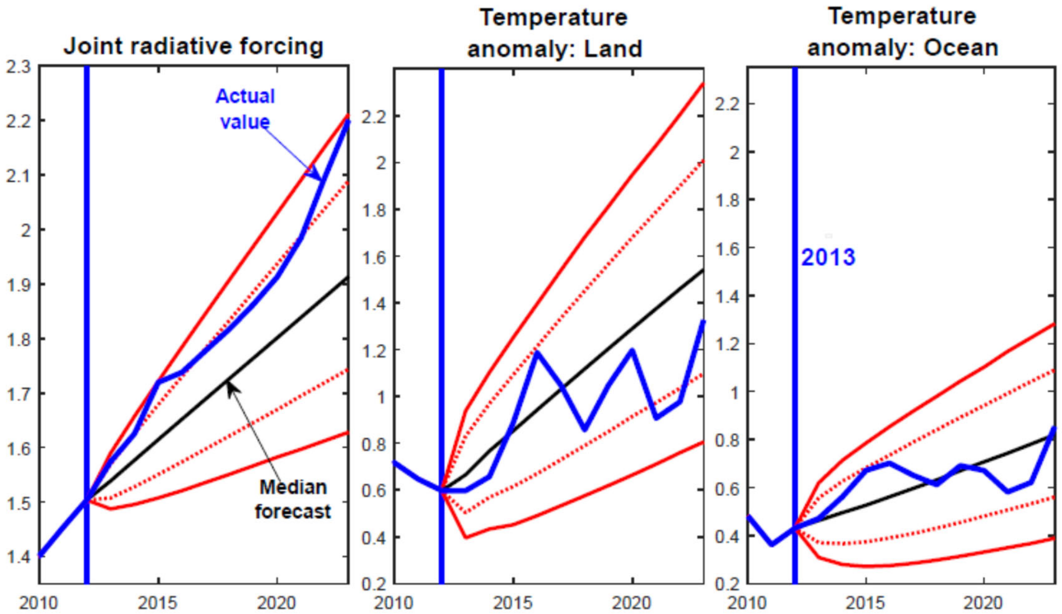


Characterize uncertainty about μ_t via Hamilton’s (*J. of Econometrics*, 1986) Monte Carlo integration procedure …

‘Freeze’ estimate of μ_t at 2023 …

Conditional on data up to 2023, simulate model forward in time until end of XXI century …

V: Out-of-sample forecasting exercise for 2013-2023



Evidence from exercise similar to that in previous slide …

Estimate model based on data up to 2013, then simulate it until 2023 …

Evolution of land anomaly since 2013 is mostly below median projection based on data up to 2013 …

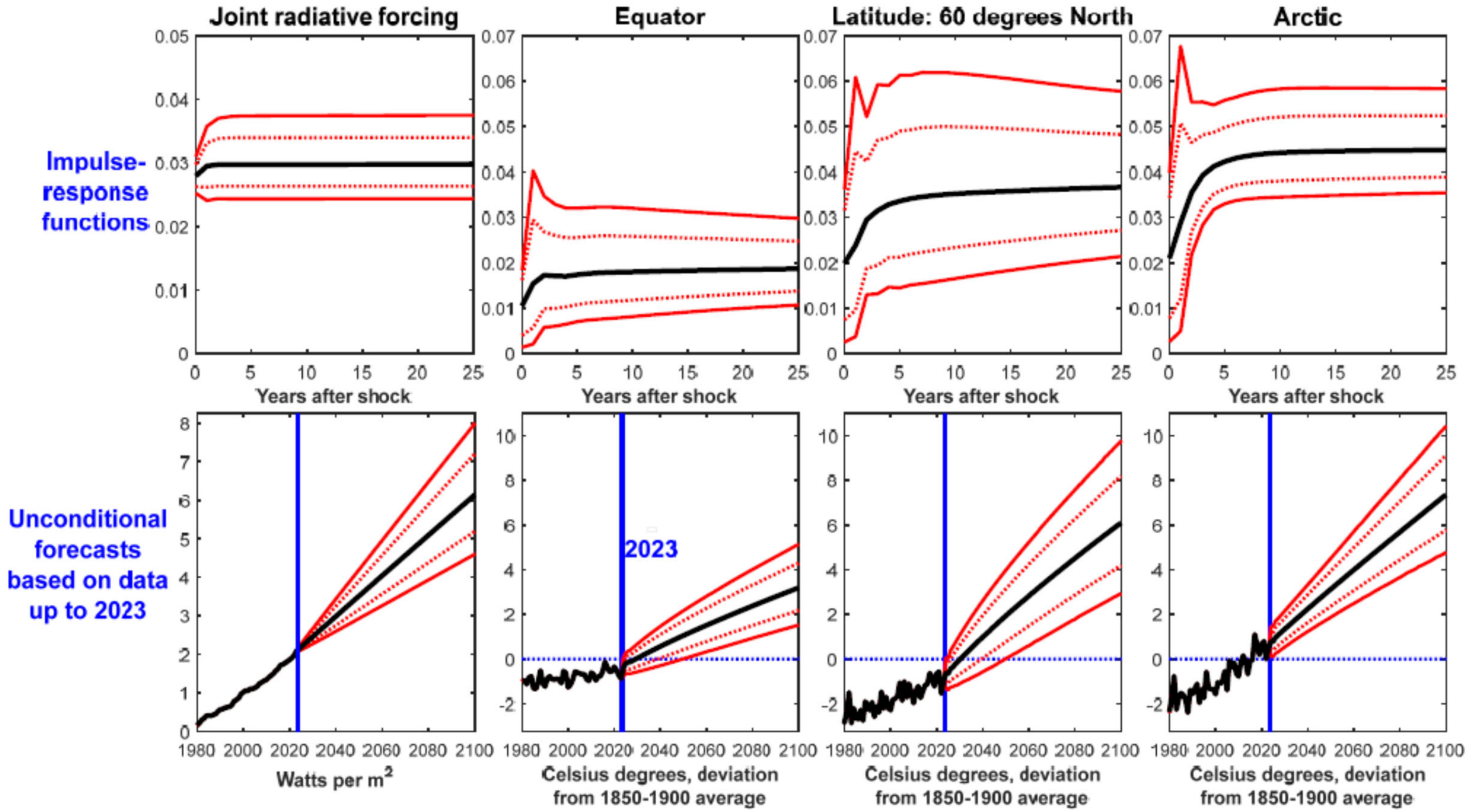
Evolution of ocean anomaly is in line with median projection …

Evolution of JRF is in upper tail of forecast distribution …

Implication: increase in JRF has been accelerating (we already saw this), and temperature anomalies still have to catch up …

2023 was shocking enough, but temperature increases already in the pipeline are even worse …

VI: Evidence for alternative latitudes

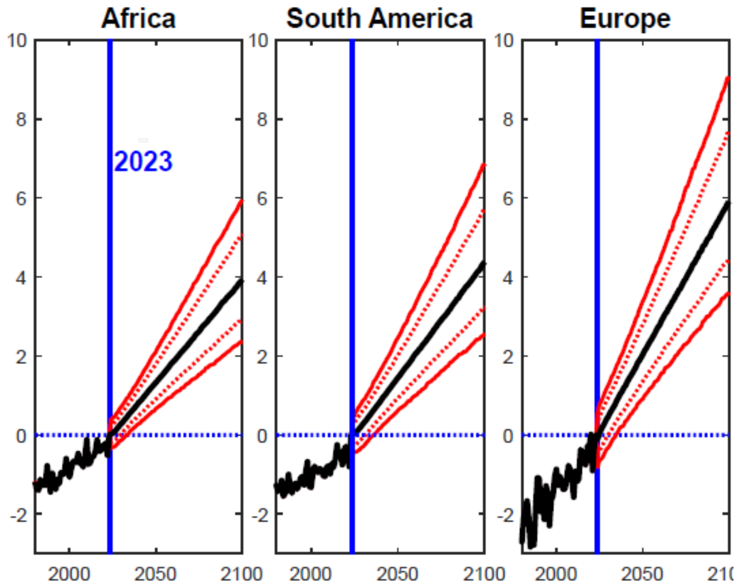


Material differences between alternative latitudes …

The higher the latitude, (1) the slower the response to JRF shocks, and (2) the largest the overall temperature increase …

What about individual continents?

VII: Evidence for individual continents



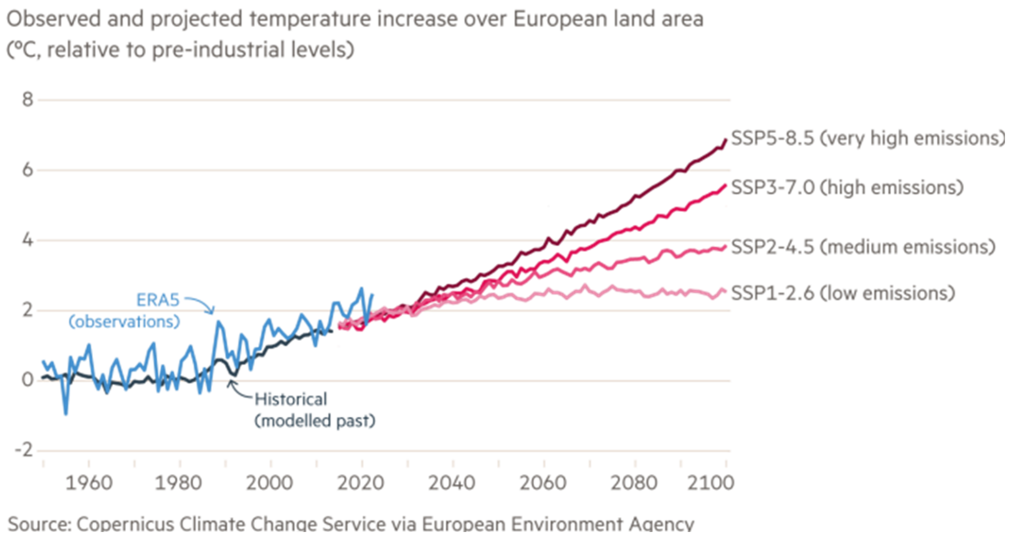
Selected evidence on the left …

Material differences between continents …

Europe is fastest-warming continent …

Africa is projected to warm by 2 Celsius degrees less by 2100 …

Projection for Europe in line with that from European Environment Agency's *Copernicus* under 'very high emissions' scenario (right), which is comparable to my 'no change' scenario …



VIII: Global projections conditional on alternative JRF paths

Compute conditional forecasts as in Waggoner and Zha (*ReStat*, 1999) …

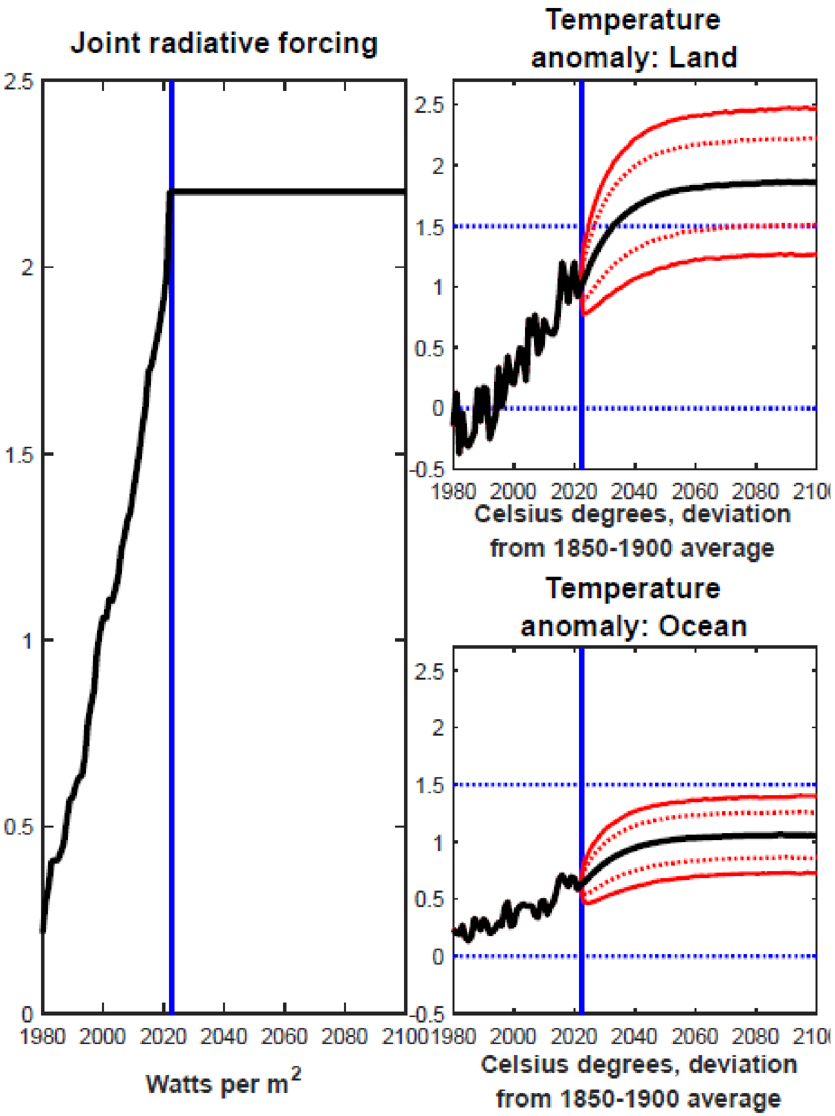
Consider 5 scenarios for evolution of JRF:

- **JRF being stabilized in either 2023 or 2050, and remaining constant after that …**
- **JRF peaking in 2050, and then being brought back, in 2100, to level of either 1990, 2000, or 2010 …**

Why making JRF peak in 2050? Removing massive amounts of carbon from atmosphere requires enormous amount of energy …

Currently, seems unlikely nuclear fusion will be available before mid-century …

I take 1.5 Celsius degrees as benchmark threshold, even if it is essentially arbitrary …

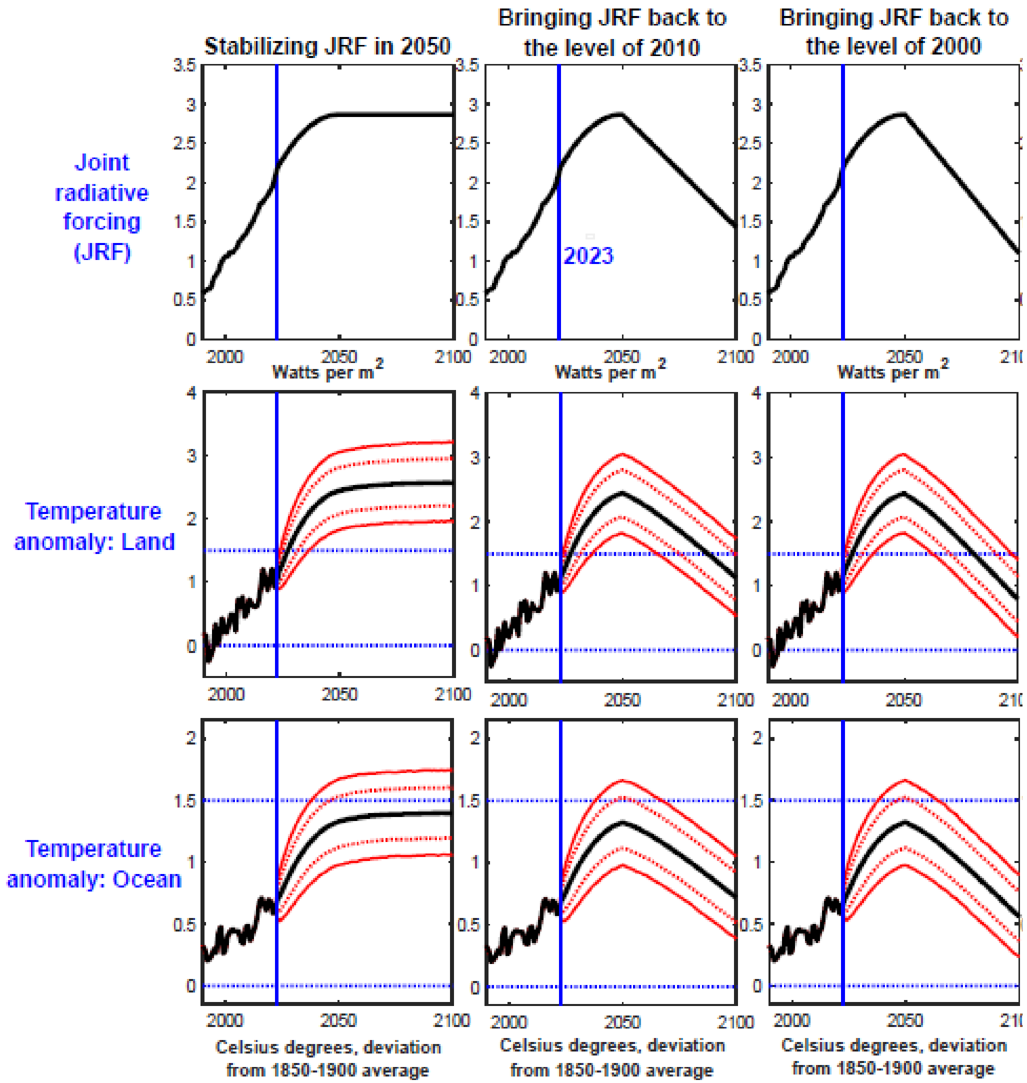


Two main findings …

(I) Even if we were able to 'freeze' JRF at 2023 level, intrinsic dynamics of system in response to previous increases points to risk of dangerous levels of warming going forward …

<u>Implication</u>: bringing climate change under control requires scaling JRF back to levels reached before 2023 …

<u>Question</u>: How much do we need to scale it back?



Evidence suggests that, given extent of uncertainty, bringing climate change under control will require bringing JRF back to level of <u>early XXI century</u> …

Some tentative conclusions: How dire is our predicament?

My own reading of overall developments leads me to be deeply pessimistic: There are 3 main reasons for this …

First, climate change is dramatically accelerating …

I showed you evidence based on oceans' temperatures, but in fact there is much worse and starker evidence …

The 2023 *Global Tipping Points Report* highlighted how, under current trajectories, the system-Earth will cross several 'global tipping points' over the next few decades:

- **collapse of ice sheets in Greenland and West Antarctica;**
- **widespread thawing of permafrost;**
- **death of coral reefs; and**
- **collapse of Atlantic Meridional Overturning Circulation (AMOC) …**

Past AMOC collapses were associated with plunge in temperatures in Europe and North America by several Celsius degrees …

Second, 'experiment' we have embarked upon since Industrial Revolution is <u>unprecedented</u> in Earth's history …

<u>Logical implication</u>: Past is not necessarily reliable guide to future …

<u>Example</u>: Carbon increase associated with Paleocene-Eocene Thermal Maximum (PETM), 55.5 million years ago, had been greater than increase (so far) since start of Industrial Revolution …

PETM increase, however, took place over period between 20,000 and 50,000 years, not 2 centuries …

Many climate scientists who are otherwise deeply worried stress that evidence from PETM shows that temperature increase will be limited to at most 'just' 5-8 degrees …

Maybe, but PETM and current 'experiment' are radically different: therefore, not clear whether PETM is informative for our future …

We simply do not know enough about how the system-Earth works: e.g., climate scientists can't explain the 2023 jump in oceans' temperatures …

In an interview with the *Washington Post* on April 19, Gavin Schmidt stated:

'What if the statistical connections that we are basing our predictions on are no longer valid? It'sniggling at the back of my brain that it could be that the past is no longer a guide to the future.'

Third, lack of urgency on the part of governments …

When, in early 1940s, it was a matter of obtaining nuclear weapons before the Nazis, Manhattan Project delivered in just a few years …

Today's challenge is equally existential: it is open question whether our civilization will be able to adapt to temperature increase by even 'just' 5 Celsius degrees within a few decades, but there is nowhere near a comparable extent of urgency …