Metamodel.blog Recent posts 2023-07-06

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1 What to expect when you're expecting a better climate model

Irreducible uncertainties associated with internal variability and human actions limit our ability to predict long-term climate change. Higher model resolution can help, but it is not a silver bullet.

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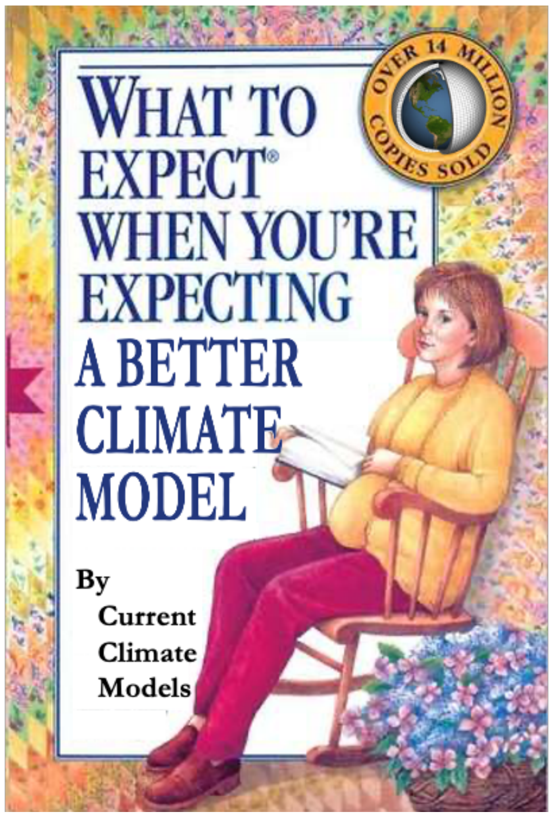


If we build a gigantic supercomputer, ask it the ultimate question, and receive a single number as an answer, what have we learned? Without context, not much. A single number, whether it is 42, as in *The Hitchhiker's Guide to the Galaxy*,[1] or 3°C for Earth's climate sensitivity, doesn't mean much unless we know how it was calculated and what its uncertainty is.

This provides a nice segue to the recent blog discussion about a concerted international effort to build a climate model with a 1-km (k-scale) horizontal grid.[2] That would be a big jump from the current generation of climate models, which typically use a 50-km grid. The common expectation is that a million-fold increase in computer power available for modeling will lead to a quantum leap in our predictive capabilities, thus better informing

[1] Warning of unprecedented heatwaves as El Niño set to return in 2023 (The Guardian), Global heat waves show climate change and El Niño are a bad combo (NPR), The unusual factors behind the extraordinary heat across the southern US (Vox.com)

[2] Occam's (or Ockham's) razor is a principle attributed to the 14th century logician and Franciscan friar William of Ockham: *Pluralitas non est ponenda sine neccesitate*, or Entities should not be multiplied unnecessarily (UCR.edu)

policy-makers. The headline of a recent Wall Street Journal article, “Climate Scientists Encounter Limits of Computer Models, Bedeviling Policy”, reflects this sentiment.[3]

To what extent can better climate models inform policies, and exactly what policies can they help inform? The phrase “actionable predictions” is frequently used in this context, but often without elaboration. How much improvement in predictions can we expect from much better climate models of the future? Will they reduce the error bar by 10%, 50% or 90%? It turns out that our current models have something to say something about that.

1.1 Limits and uncertainties of climate prediction

From our familiarity with weather forecasts, we know there are limits to weather prediction. We don’t expect forecasts to be accurate beyond about a week. That’s because we have imperfect knowledge of the initial condition for a weather forecast. Small errors in the initial condition grow exponentially over time leading to large errors in the forecast after several days. This property of chaos, known as the Butterfly Effect, limits weather prediction to about two weeks. Even a perfect weather model cannot predict beyond this limit.

Is there a corresponding limit to climate prediction? The usual answer is that the Butterfly Effect does not apply to climate prediction because we are not predicting individual weather events but the statistics of future weather. That’s technically true, but what happens to the Butterfly Effect beyond two weeks? The error associated with the Butterfly Effect eventually stops growing and saturates in amplitude, morphing into *stochastic uncertainty* or *internal variability* in climate prediction. Since we can never be rid of it, we could call it the Cockroach Effect. Even that may be misleading because we could reduce roach numbers with pesticides but the stochastic uncertainty is fundamentally irreducible—it will persist even in a perfect climate model. We can estimate the amplitude of stochastic uncertainty by carrying out climate predictions with different initial conditions.

You may not have heard much about stochastic uncertainty because it’s not important when predicting global average temperature, which dominates popular discussions of global warming. Predicting societal impacts, or even tipping points, requires prediction of regional climate, which is where stochastic uncertainty becomes important. (If ice sheet instabilities and/or oceanic overturning circulation instabilities turn out to be more important on centennial timescales than currently believed, that will likely increase the amplitude of global chaotic/stochastic uncertainty.)

There are two further uncertainties in climate prediction, and they do affect global average temperature.[4] The next is *scenario uncertainty*. This arises from unpredictable human actions that determine the scenario of future carbon emissions and thus the magnitude of the resulting global warming. This uncertainty cannot be characterized probabilistically and is scientifically irreducible. Even a perfect climate model will exhibit this uncertainty—only human actions (including technological developments) can reduce it. We estimate this uncertainty by carrying out predictions with different emission scenarios.

The third uncertainty in climate prediction is *model uncertainty* which arises from structural differences in the representation of small-scale processes like clouds in climate

[3] Ch.7, The Climate Demon: Past, Present, and Future of Climate Prediction (ClimateDemon.com)

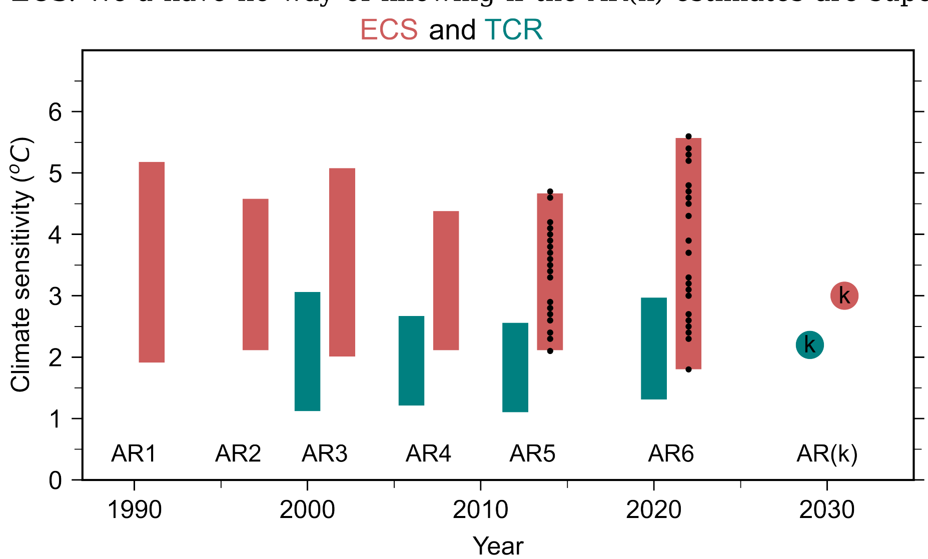
[4] Is the weather actually becoming more extreme? (TED.com), The Butterfly Effect: Everything You Need to Know About This Powerful Mental Model (FS.blog)

models. Since these processes occur on scales too fine to be resolved by the coarse spatial grids of the climate, they are represented using approximate formulas known as parameterizations. The errors in these parameterizations lead to spread in predictions using different models. This is the only scientifically reducible error in climate prediction. Using a model with a finer grid, such as a k-scale model, can decrease this uncertainty because fewer processes will be poorly represented. We estimate this uncertainty by carrying out predictions with climate models using different parameterizations.

1.2 Meta-prediction: Predicting the future of prediction

Analyzing the partitioning between the three different types of uncertainty in our current models allows us to calibrate our expectations for better models. Two important measures of how quickly the globe might warm are transient climate response (TCR) and equilibrium climate sensitivity (ECS). These two measures are basically rough estimates of how much warming doubling of carbon dioxide will cause by the end of this century and over many centuries, respectively. As we see in Figure 1, the spread in these measures has not decreased as the models have gotten "better" over the years. If anything, the ECS spread has increased in recent decades. Figure 2 shows the multi-model average of the global warming projected for three different emission scenarios. The error bars show the model uncertainty for each scenario. Note that the scenario uncertainty is comparable to, or larger than, the model uncertainty.

New let us perform a thought experiment. Suppose we have a future IPCC Assessment Report AR(k) based on a single k-scale model. That means we have a model that predicts climate out to year 2100 using a 1-km spatial grid. As we see in Figure 1, we would have an additional estimate each for TCR and ECS, respectively. But without multiple independent k-scale models, we cannot assess the model uncertainty, i.e., the spread in TCR or ECS. We'd have no way of knowing if the AR(k) estimates are superior in any



sense.

Figure 1. *Model-simulated values of equilibrium climate sensitivity (ECS; red) and transient climate response (TCR; teal) from successive IPCC Assessment Reports from AR1 to AR6. The bars show the spread of values estimated by different models, with black dots showing individual model values for AR5 and AR6. The solid circles show ECS and TCR value assessed for a hypothetical IPCC AR(k) in 2030 using a single k-*

scale model. [Adapted from Meehl et al. (2020)][5]

Let us be optimistic and assume further that we are able to afford to run many independent k-scale models for the hypothetical IPCC AR(k) and the spread between these models has reduced by a factor of 2 (say). As we see in Figure 2, the spread in predicted warming by 2100 for different scenarios will become the dominant uncertainty, and will persist even if we had the perfect climate model. Mitigation policy decisions will not benefit very much from reduced model uncertainty or narrower estimates of climate sensitivity, because scenario uncertainty dominates. When it comes to predicting how much the globe will warm by the end of the century, *the biggest uncertainty is us*.[6]

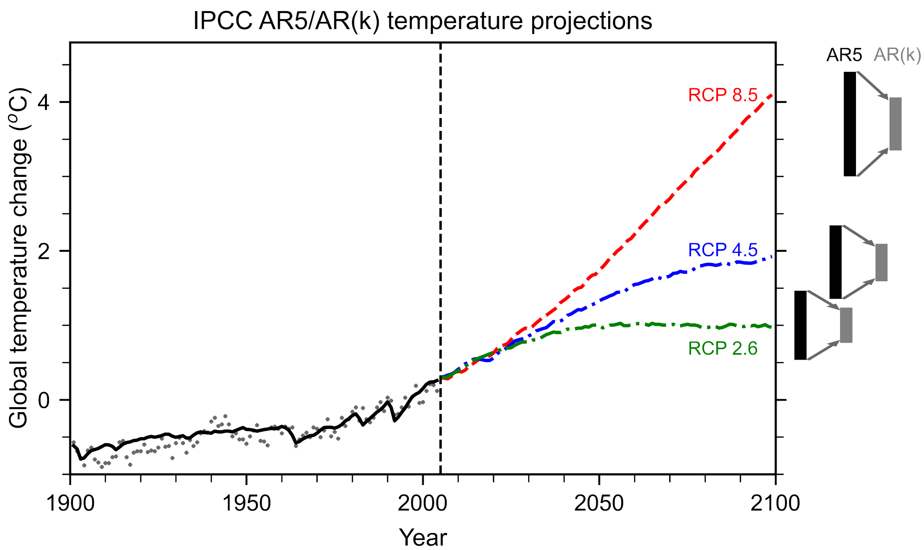


Figure 2. *IPCC AR5 multi-model average prediction of global-average surface temperature for three emission scenarios, high-end (RCP8.5; red), medium (RCP 4.5; blue) and low-end (RCP 2.6; green). The black bars show the AR5 model uncertainty, or the spread amongst models; the gray error bars show what it would look like if the spread was reduced by a factor of 2 by better models in the hypothetical AR(k). (AR5 projections are shown rather than AR6, because AR6 uses model weighting to shrink its larger error bars to resemble AR5 anyway.)* [Adapted from Knutti and Sedlaček, 2013][7]

The dominance of scenario uncertainty for centennial prediction of global temperature is illustrated more vividly by the evolution of the uncertainty partitioning over time (Figure 3a). Scenario uncertainty grows monotonically but is relatively small for the first decade-and-a-half of the prediction, while model uncertainty peaks around that time. Therefore, reducing model uncertainty would have the biggest (fractional) benefit for global predictions on decadal timescales.

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[5] When the Butterfly Effect Took Flight (MIT Technology Review)

[6] Anatomy of a heat wave (theclimatebrink.substack.com)

[7] Assessment of Historic and Future Trends of Extreme Weather in Texas, 1900- 2036, 2021 Update. Document OSC-202101 (J Nielsen-Gammon et al., 2021:, Office of the State Climatologist, Texas A&M University)

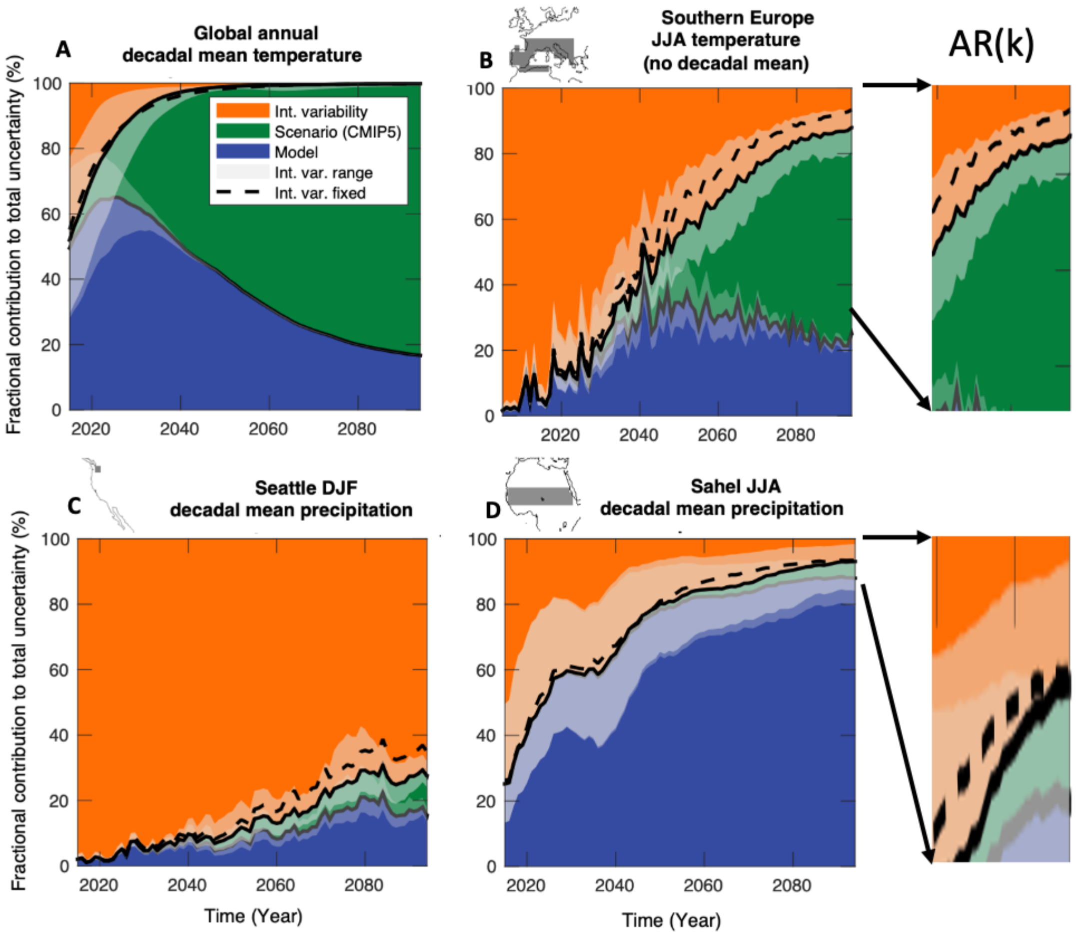

Figure 3. *Partitioning of the uncertainty (stochastic/internal-orange; scenario-green; model-blue) for decadal-average model predictions of: A. Global-average surface temperature; B. summer (Jun-Jul-Aug) temperature over southern Europe (no decadal average); C. winter (Dec-Jan-Feb) precipitation in Seattle, Washington (USA); D. summer (Jun-Jul-Aug) rainfall over the Sahel region of Africa. The lighter shading denotes the higher-order uncertainty in model estimates of stochastic internal variability. If we had a perfect model, the model uncertainty fraction (blue) would vanish, but other uncertainties would remain. The two "blow-ups" on the right illustrate this for a hypothetical AR(k) with greatly reduced model error.* [Adapted from Lehner et al., 2020][8]

Improved prediction of just the global averages is not very useful for assessing societal impacts, which depend on the details of regional climate change. Say we are interested in predicting summer temperatures in southern Europe. The dominant uncertainty is associated with the emission scenario (Figure 3b). Model error accounts for only 30% of the prediction uncertainty. That means even a perfect model would reduce the total uncertainty by no more than 30%. (The regions where we can expect model improvements to provide the most "bang for the buck" are those where model error is the dominant uncertainty and emission scenarios are the second-most important uncertainty, such as over the Southern Ocean.)

[8] Strange weather in the multiverse of climate (Metamodel.blog)

Next, we consider two regions with contrasting behavior for regional precipitation prediction: the rainy city of Seattle in Washington state, USA and the dry Sahel region of Africa (Figures 3c,d). In both regions, the scenario uncertainty fraction is small, but the model uncertainty fraction is quite different.

If we are interested in predicting Seattle rainfall for the end of the century, current models tell us that better models may not make much of a difference—unpredictable and irreducible stochastic uncertainty accounts for over 70% of the total, meaning that rainfall changes will remain hard to predict (Figure 3c).

Predicting Sahel rainfall for the end of the century tells a different story (Figure 3d). Spread among different models plays a dominant role in the uncertainty. This is the manifestation of a common problem in climate modeling—the large biases in the simulated climate in certain regions. The focus on global average temperature often masks these large regional biases. Higher resolution models would definitely be helpful in reducing these biases.

What if k-scale models were able to substantially reduce the model spread in the Sahel region? Figure 3d suggests that this would cause internal variability to become the dominant uncertainty in the Sahel region. With a better model, Sahel rainfall may still be mostly unpredictable on centennial timescales, but we will be able to say that with more confidence and a much smaller error bar.

We have considered changes in time-averaged temperature and rainfall. But extremes in temperature and rainfall are also very important because they can have severe impacts. Currently, our coarse-resolution climate models cannot predict rainfall extremes very well, because rain is determined by small-scale air motions and microphysical processes. With finer resolution and parameter tuning, k-scale models should be able to do a better job of simulating these extremes in our current climate. The extent to which k-scale models can better predict how rainfall extremes will change in a future climate is an open question—it will depend upon how big a role uncertainties in the still unresolved microphysical processes will play.

1.3 Deconstructing the promise of k-scale

We have outlined what we might expect from better climate models with regard to reducing uncertainty. Now we consider the two recent *Nature Climate Change* articles about k-scale modeling that triggered the blog discussions, one about the atmosphere and the other about the ocean. Their titles are:

1. *Ambitious partnership needed for reliable climate prediction* (ATM)[9]
2. *The small scales of the ocean may hold the key to surprises* (OCN)[10]

As is often the case in climate discussions, ambiguities in language can lead to a mismatch between what the public thinks that science can deliver and what the science is actually capable of delivering. Therefore, it is worth deconstructing what these articles actually say about the benefits of k-scale modeling.

For example, consider the phrase "climate prediction", which appears in the title of the ATM article. Climate scientists use this phrase even for predictions of the average

[9] Who's afraid of the Big Bad El Niño? (Metamodel.blog)

[10] "Widespread observed and projected increases in the intensity and frequency of hot extremes, together with decreases in the intensity and frequency of cold extremes, are consistent with global and regional warming." p.1523, IPCC AR6 WG1 Report

weather for the next season, because climate is the average weather. But the public is more likely to associate "climate prediction" with IPCC and predictions of global warming extending to the end of the century (absent additional qualifiers like "seasonal climate prediction"). This conflates two very different types of prediction: one where initial conditions provide the signal and another where they become the noise.

The ATM article talks about reliable predictions from "daily weather to decadal variability, conditioned by global warming trends". Reliability cannot be assessed for centennial timescale predictions, due to lack of data. Therefore, the article seems to be implicitly focusing more on reducing model biases to improve predictions of El Niño and other phenomena up to the decadal timescale. This is the timescale where reducing model uncertainty will be most beneficial in improving global predictive skill (Figure 3a).

K-scale models should be able to better predict the future statistics of local extreme events on shorter timescales because they can resolve fine-scale fluid motions associated with cloud processes. On longer timescales, however, errors in other non-fluid components of the climate system—such as microphysical processes in clouds or the carbon cycle—will play an increasing role. The direct benefit of k-scale modeling in reducing the uncertainty of centennial climate predictions would therefore be more limited. There would still be the indirect benefit of increasing our confidence in such long-term climate predictions.

The OCN article, on the other hand, does not even mention predictions and instead talks about projections, implying longer timescales. (The title actually refers to "surprises", which is quite the opposite of prediction.) Higher resolution can improve ocean simulation in critical regions that affect possible tipping point behavior associated with Atlantic ocean circulation. Current comprehensive climate models do not exhibit tipping points, but it is possible that higher resolution models could exhibit more nonlinear or threshold behavior. The suggestion, therefore, is that current models could be underestimating oceanic internal variability.

Despite their contrasting views on prediction, the common thread in both articles is the utility of higher spatial resolution to reduce biases in models and improve our understanding of the climate system. This will improve our confidence in climate predictions but should we expect it to significantly reduce the spread in predictions?

Our everyday experience with prediction comes from weather forecasts. We expect that a better weather model using more powerful computers will make predictions with a smaller "error bar". This error bar, which we can calculate using past observations, has indeed decreased over time with better weather models.

Climate prediction is fundamentally different. Since centennial-scale global warming is an unprecedented event, we cannot use observational statistics to compute its error bar.[11] Therefore, the same climate models that make predictions are also used to estimate the spread or the "error bar" associated with their predictions. Better climate models can give us more knowledge because more processes are added or represented better, but the associated error bar could be larger. More knowledge may not always lead to more certainty![12]

[11] The Texas Power Grid Failure Is a Climate Change Cautionary Tale (TIME.com)
[12] Global warming above 1.5C could trigger 'multiple' tipping points (CarbonBrief.org)

1.4 One model to rule them all?

Contrary to some media headlines, it's not the lack of better models that bedevils climate mitigation policy, but the lack of political will. More computing power for models can help improve the skill of short-term (seasonal-to-decadal) predictions, but that would not be relevant to climate policy.

The understanding gained from better short-term predictions can help improve models used for long-term prediction by reducing biases, especially in their precipitation simulations. Depending upon the relative strengths of internal variability and model error in each region, these improvements may or may not significantly reduce the quantified uncertainty of long-term prediction (Figure 3). Nevertheless, better models would increase our confidence in long-term predictions and provide a sounder basis for climate adaptation policies.

The ATM article recommends spending certain dollar amounts to support k-scale modeling, but doesn't spell out exactly how they should be spent. Should the money be used to build a giant supercomputer associated with a single, international modeling center, or should it be distributed among many centers? Let us consider the former option, i.e., creating the climate-equivalent of CERN, the international facility dedicated to experimental particle physics with an order of magnitude more resources than any national facility:

- *A single k-scale CERN for centennial climate prediction*: This would be a bad idea. Such a Climate-CERN will gain de facto authority because its model will be considered "better" and its climate prediction will be considered official. Since it will contribute only one data point in Figure 1, there'll be no way to estimate the error spread. Of course, the Climate-CERN could develop multiple model structures to estimate the spread. But to do that well, it may require at least 10-20 different model structures. It would be better for these model structures to be developed at separate modeling centers under independent management. (As anyone who has worked at a modeling center could tell you, human factors affect the choice of model structure as much as scientific factors.) Collaboration and standardization of coding structure between multiple modeling centers would certainly be beneficial. Sharing a single supercomputer to run independent models would also be fine.
- *A single k-scale CERN for seasonal-to-decadal prediction*: This could be a good idea, serving as a proof-of-concept for the touted benefits of k-scale modeling. The goals and performance benchmarks of such a SeaDec-CERN would need to be clearly defined, to avoid "mission creep". Limiting predictions to shorter timescales would also prevent the dilution of computing resources. The short-term predictions would provide public benefits, but may not help mitigation or adaptation policies. A SeaDec-CERN may also gain authority because it has a "better" model, but there's a self-correcting mechanism. We'll know soon if the k-scale El Niño forecasts are substantially better than competing models with fewer resources. If they are not, which is quite possible, then SeaDec-CERN will lose its authority. If the forecasts improve substantially, then the knowledge gained can help reduce biases in long-term climate prediction models.
- *Black swans, unknown unknowns, and fundamental research*: We have focused so far on what to expect from better models. But what is unexpected—the "surprises" alluded to in the OCN article—could be more interesting. We know that our climate models are imperfect representations of the complex climate system. In our

climate future, we may encounter a black swan event that was never anticipated or cross a tipping point that was unpredictable. Having the most comprehensive model, *but not necessarily the most complex model*, would help us be better prepared when we encounter unknown unknowns. A good example is the discovery of the Antarctic ozone hole.[13] Without good atmospheric chemistry models that were already available, it would have taken us much longer to understand the mechanism of the ozone hole. Even though these models never predicted the emergence of the ozone hole, they could be modified to predict its future evolution. Model development for the sake of better understanding is typically considered fundamental research, because it does not provide "actionable predictions". Rather than be obsessed with predictions, one can argue that it is important for society to support fundamental climate research as a form of planetary defense—on par with, or even exceeding, other big science projects like space-borne telescopes, planetary missions, and particle accelerators.

Note: As noted in a blog comment, an international center for long-term climate prediction that builds a model at current spatial resolution may be justified for a very different reason. Scientists from developing countries lack the resources to build and use climate models to answer questions that are most relevant to them. Having an international climate modeling center dedicated to their needs would be a great idea!

1.5 Comments

Note: For updated comments, see the original blog post and the anouncement tweet.

- *R Saravanan*:
  Important paper about uncertainty in predicting climate extremes:
  For precip extremes, "past observations … can provide almost as accurate a picture of future extreme occurrences as even the best … climate models.."
  "large ensembles should become the standard" for models
  Tweet thread

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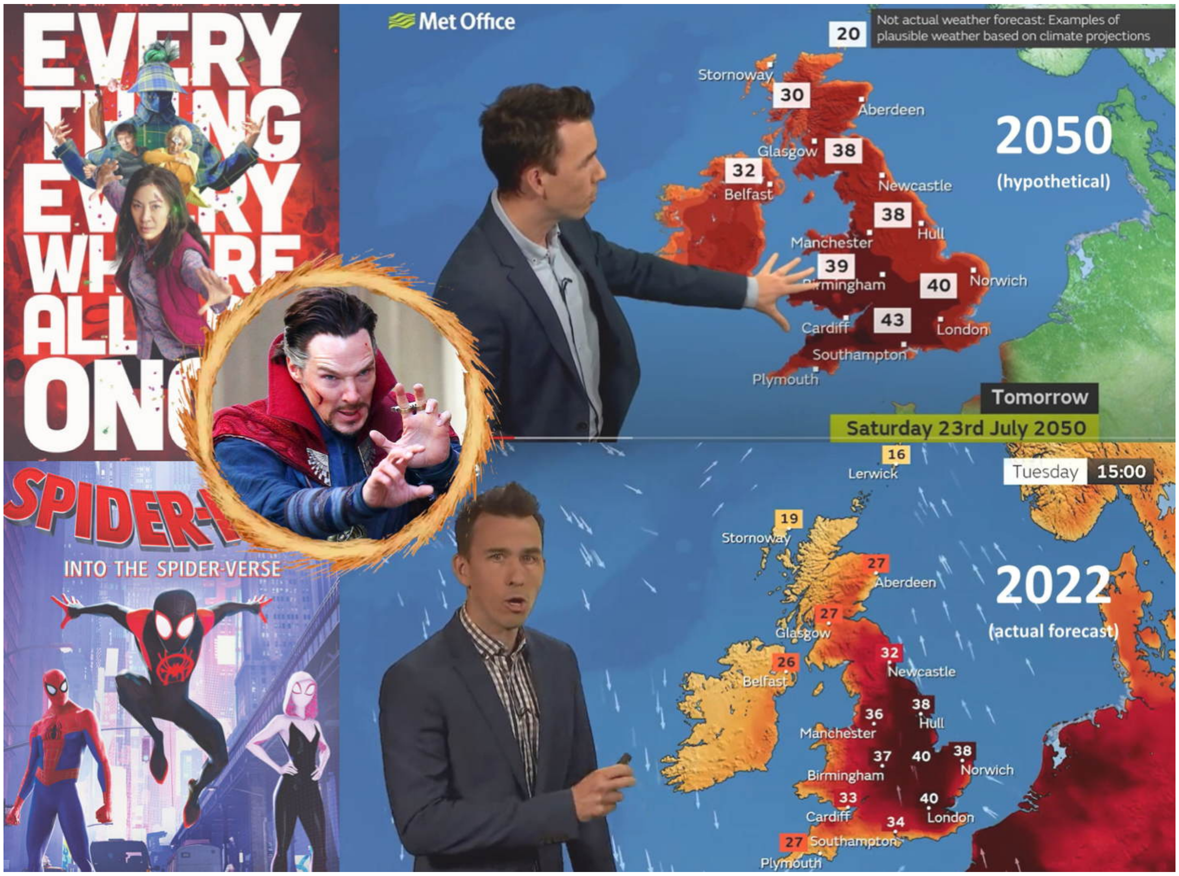
2 Strange weather in the multiverse of climate

We cannot predict our weather universe but we can choose our emission multiverse

Metamodel.blog 2022-08-02

[13] Damage Functions (or Why I am Mad at Climate Economists)](https://lpeproject.org/blog/damage-functions-economics-climate-science/)



Imagine that our universe is just one slice of bread in the grand cosmic loaf of the multiverse.[14] That's a popular description of the physics concept of the multiverse. But the multiverse is not considered essential for everyday applications of physics, even if it makes for good pop-sci narratives. If one were to use Occam's Razor to slice up the multiverse loaf, one could even argue that the concept of the multiverse adds unnecessary complexity.

Although it may be speculative in physics, the multiverse can be quite useful in understanding climate prediction. We usually define climate as the time average of weather, typically over thirty years or so. When climate itself is changing over that period, this definition becomes less useful. Enter the multiverse.

Imagine that our weather universe is just one slice of bread in the grand loaf of the climate multiverse. The same weather events—like heat waves or hurricanes—occur across the multiverse, but in a different order in each weather universe. We can then define climate as the average across the multiverse. As climate changes over time, the multiverse average also changes.[15] We cannot predict which weather universe we will live in, but we can try to predict the average properties of the multiverse we will live in. This is a complex scientific concept that is often hard to explain to a lay audience.

[14] Warning of unprecedented heatwaves as El Niño set to return in 2023 (The Guardian), Global heat waves show climate change and El Niño are a bad combo (NPR), The unusual factors behind the extraordinary heat across the southern US (Vox.com)

[15] Occam's (or Ockham's) razor is a principle attributed to the 14th century logician and Franciscan friar William of Ockham: *Pluralitas non est ponenda sine neccesitate*, or Entities should not be multiplied unnecessarily (UCR.edu)

Thankfully, the slew of recent movies about the multiverse, or multiple versions of the universe, may make it easier.

Although other sci-fi movies have relied on the multiverse before,[16] *Spiderman: Into the Spider-Verse* was the first to use it in its title. If you are into Marvel blockbusters, watching *Spiderman: No Way Home* or *Dr. Strange and the Multiverse of Madness* is good preparation for this blog post about the climate multiverse. If you prefer something more arty (or downright weird), then surviving a viewing of *Everything Everywhere All at Once* may be even better preparation. (After all, climate models have been described as trying to predict everything everywhere all at once.[17])

Not appreciating the multiverse aspect of climate prediction can lead to confusion about the impact of climate change on extreme weather. In July 2022, Britain experienced unprecedented heat waves, with temperatures exceeding 40°C in some locations. Ironically, in 2020, the UK Met(eorological) Office had predicted a similar heat wave as hypothetically occurring in July 2050, using computer models, as part its forecasts from the future program (Figure 1).[18] Does the fact that such a strong heat wave occurred 28 years earlier than "predicted" mean that our climate models are underpredicting the severity of climate change? That is indeed one possible explanation. But there is an alternative explanation—and that involves the multiverse.

[16] Ch.7, The Climate Demon: Past, Present, and Future of Climate Prediction (ClimateDemon.com)

[17] Is the weather actually becoming more extreme? (TED.com), The Butterfly Effect: Everything You Need to Know About This Powerful Mental Model (FS.blog)

[18] When the Butterfly Effect Took Flight (MIT Technology Review)

Figure 1 *Top panel shows a hypothetical heat wave forecast for 23 July 2050 (as simulated on a model) that was published in 2020 by the UK Met Office. Bottom panel shows the actual heat wave forecast for 19 July 2022.* [From a tweet][19]

2.1 A multitude of multiverses

If we had a perfect model of the universe and perfect knowledge of its current state, could we predict the future perfectly? Philosophers once believed this was possible, and they named the super-intellect that could make such a prediction as Laplace's Demon.[20] Laplace's Demon could predict the future of our single universe, and there

[19] Anatomy of a heat wave (theclimatebrink.substack.com)

[20] Assessment of Historic and Future Trends of Extreme Weather in Texas, 1900- 2036, 2021 Update. Document OSC-202101 (J Nielsen-Gammon et al., 2021:, Office of the State Climatologist, Texas A&M University)

would be no need to invoke the multiverse. However, quantum uncertainty and classical chaos dashed the prospects of there being a Laplace's Demon, opening the door to the multiverse of predictions.

We only have imperfect models of a subset of the universe, called climate models, and we can never measure the current state of the climate perfectly. Therefore, we can never predict the future perfectly. To account for our imperfect knowledge, we predict the future of a multiverse, rather than our single real universe. The hope is that the set of future predicted universes, the predicted multiverse, includes the future of our real universe.

In climate prediction, we deal with three types of multiverses (Figure 2). The first type is the *weather multiverse*. Since we do not know the initial climate state perfectly, we carry out predictions for several slightly different initial states. Due to the Butterfly Effect of chaos, even minor differences in the initial state will lead to completely different weather conditions after a few weeks, generating the weather multiverse.

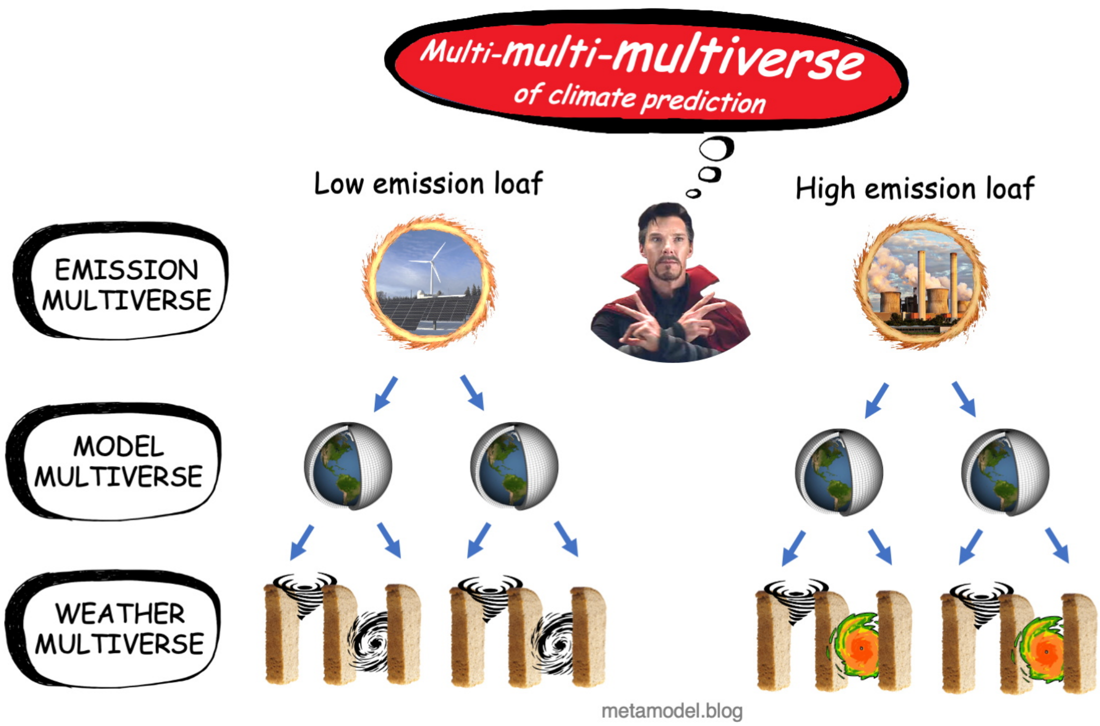


Figure 2 *Three types of multiverses in climate prediction. The bread slices at the bottom represent different predicted universes with random sequences of weather events. Assuming our models are good, the real universe will be one of those slices, but we can never tell exactly which one. By controlling emissions, we select the loaf that the slice will be chosen from. (The color of the hurricane graphic in the high emission loaf indicates that some weather events will be stronger in a warmer world.)*

Say we make a prediction starting from 2020 using a climate model. One predicted universe may have an extreme heat wave (with 40°C temperatures) occurring in July 2050, but another predicted universe may have it occurring in July 2022 (Figure 1). If we simulate only a few predicted universes, then we may miss out on the one where the heat wave occurs earlier. This could explain why the UK Met Office made a hypothetical prediction of the extreme heat wave in July 2050, but a real event occurred much earlier.

The larger the weather multiverse, the more likely that it includes the real universe. It has been estimated that we may need 50 or more universes in the weather multiverse to adequately span the range of weather variations.[21]

There can be another reason the extreme heat wave occurred earlier in the real universe than in the predicted multiverse. If the climate model is imperfect, and tends to systematically underpredict the warming, then even a larger multiverse may not capture the extreme heat waves. To handle model imperfections, we need another type of multiverse, and we can call it the *model multiverse*. We construct several climate models, each with somewhat different structures for scientific equations. The expectation is that while some models may underpredict the warming, others will overpredict it to compensate. For example, one model may predict that the Arctic will be ice free by 2050 whereas another may predict slower Arctic ice loss. We carry out predictions with different climate models to generate the model multiverse.

There is the need to invoke yet another multiverse type. Our climate models represent just a subset of the universe, because they predict only the physical, chemical and biological aspects of the climate system using scientific equations. But the rest of the universe also affects climate. This includes human activities resulting in carbon emissions. There are no scientific equations to predict human actions a century into the future. So we simply make different sets of plausible assumptions, called *scenarios*, about how humans may behave in the future and then calculate the resulting carbon emissions. Thus we generate the *emission multiverse*, where we predict the future for different carbon emission scenarios.

To top it all, the three types of multiverse are not additive; they are multiplicative (Figure 2). Say there are 50 universes in the weather multiverse, corresponding to different initial states. We may have 20 different equation structures in the model multiverse. We may choose 4 scenarios for the emission multiverse. This means that all the loaves in the grand multi-multi-multiverse of climate will have a total of $50 \times 20 \times 4 = 4000$ slices, each corresponding to a different predicted universe!

2.2 Risk assessment and the multiverse

To properly assess climate risk, we need to consider all three types of multiverses. This can be quite complicated, rather like a cross between the multilayered plot of the movie *Inception* and the multiverse plot of *Everything everywhere all at once*.

Quantitative risk assessment requires assigning probabilities to each universe in a multiverse. For the weather multiverse, we can assume an equal probability or likelihood for each universe, because the memory of the initial state is quickly lost and the distribution becomes random. That's why impact risk assessment using past weather data can be quite accurate up to a decade or so, when climate change effects are still small. We don't need to consider different emission scenarios because the scenarios would not yet have diverged sufficiently. We may still need to consider different models, but global model errors would still be small because they haven't yet had time to build up.

Beyond a few decades, risk assessment gets more complicated because the different emission scenarios diverge and global model errors build up. *Purely probabilistic assessment of risk is no longer possible*, because we cannot assign objective probabilities to the different model or emission multiverses.

[21] Strange weather in the multiverse of climate (Metamodel.blog)

For model differences, we can assess the spread of among the models but we cannot assign a specific likelihood to a model universe that is appropriate for all predicted variables. For emissions, we can consider the worst-case scenario, the best-case scenario, and a few scenarios in between. Risk assessments frequently consider just a single, typically the worst-case, emission scenario rather than the full emission multiverse. This can be misleading because it could lead to the worst-case scenario being treated as the most likely scenario, by default.

Often, risk assessments ignore the weather multiverse, even though it is usually the largest of the three multiverses, because it is not important for predicting global average temperature.[22] But accurate risk assessment requires consideration of regional climate change, not just the global averages. Models also continue to exhibit large errors in their simulation of regional climate, underscoring the need for a sufficiently large model multiverse to assess uncertainty. Trimming (or ignoring) the weather/model multiverse types can lead to underestimation of the spread in risk, especially for climate impacts that depend nonlinearly on temperature or rainfall.

2.3 Extreme weather in the multiverse

In recent years, it has become increasingly common to attribute individual extreme and unprecedented weather events, such as heat waves, cold spells, droughts, floods, or hurricanes, to climate change. How do we scientifically make this attribution? To answer that, we need to consider not just whether the event is extreme or unprecedented in our weather universe, but also whether it is so in the multiverse.

Consider five simulated weather universes for the period 1950—2100 using a single climate model for a high emission scenario. Figure 3 shows the predicted occurrence of extreme hot days in Dallas, Texas, during the month of July. We see that the likelihood of extreme hot days increases as global warming continues unabated, but their occurrence is quite irregular among the different universes. Inhabitants in the top universe may be less worried about climate change in 2022, because they experience fewer extreme hot days than inhabitants in the bottom weather universe, although both suffer the same amount of global warming.

[22] Who's afraid of the Big Bad El Niño? (Metamodel.blog)

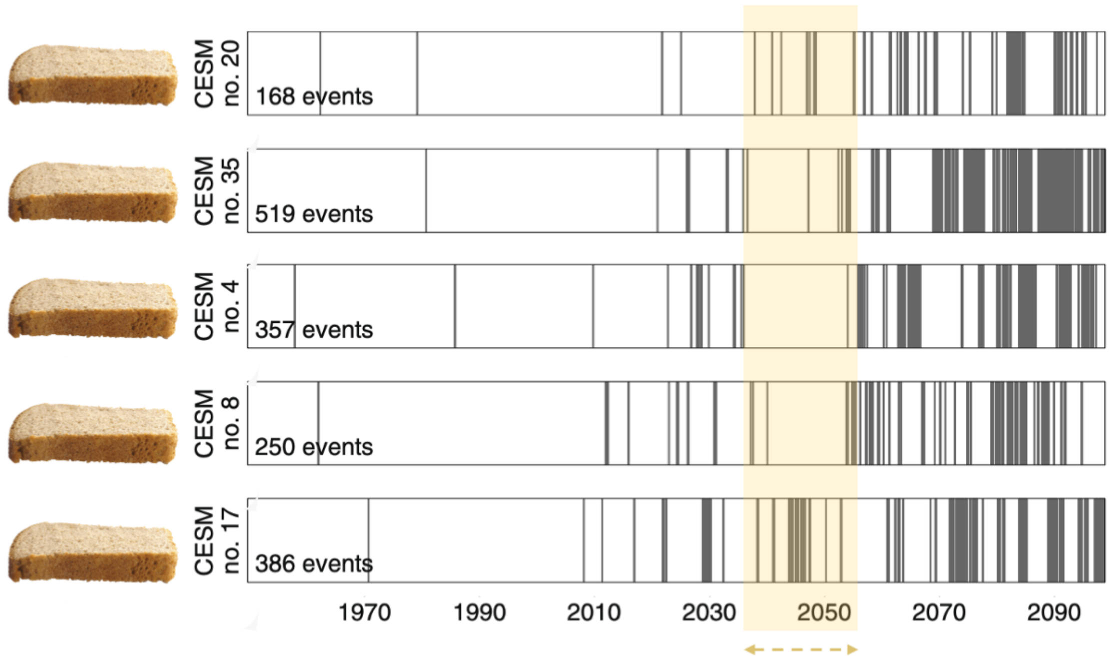


Figure 3 *Occurrence of extreme summer heat in the weather multiverse, with each bread slice denoting a single universe. Vertical bars mark the occurrence of July days that exceed the historical (1950–1999) 99.9th temperature percentile for the model grid box containing Dallas, Texas, in five simulated weather universes of the CESM climate model between 1950-2100, under a high emission scenario (RCP 8.5; now considered implausible). Lightly shaded region denotes the period 2035—2055. (Note that exceeding the monthly 99.9th percentile is roughly a one-in-30-year event before 2000 but happens more frequently later.)* [Adapted from Deser et al., 2020][23]

Note that even a decade from now, between 2035—2055, the middle universe experiences few extreme hot days (Figure 3), which could lead its inhabitants to conclude that global warming isn't affecting Dallas. But the inhabitants of the bottom universe, which experiences many extreme hot days, would draw a different conclusion. This underscores how the randomness of weather can dominate locally, even as the average temperature warms globally.

The rareness and irregularity of extreme events, as illustrated in Figure 3, means that we should carry out careful statistical and modeling analysis before reaching conclusions about the relationship between global warming and local weather. We should not just rely on our personal intuition or experience to draw such conclusions.

There is an international organization of scientists, the *World Weather Attribution* (WWA), that carefully analyzes extreme weather events. The WWA has concluded that global warming makes all heat waves more frequent, as was indeed the case with the 2022 UK heat wave.[24] Rainfall is also becoming more intense, although it is often harder to quantify exactly by how much. For some other types of extreme events, such as droughts, climate change may not always be a major factor.

[23] "Widespread observed and projected increases in the intensity and frequency of hot extremes, together with decreases in the intensity and frequency of cold extremes, are consistent with global and regional warming." p.1523, IPCC AR6 WG1 Report

[24] The Texas Power Grid Failure Is a Climate Change Cautionary Tale (TIME.com)

Climate change did not significantly affect the 2021 drought in Southern Madagascar, according to the WWA, even though some media headlines claimed otherwise.[25] Extreme cold spells are also frequently blamed on climate change, even though the scientific argument for changes in the polar vortex amplifying cold spells is far from settled.

Global warming makes many extreme weather events more frequent and intense. Drawing public attention to climate change by linking it to extreme weather is therefore a good thing. But just as we shouldn't consume too much of a good thing like sugar, we should also be wary of "overattribution" of extreme weather. Reflexively and dramatically blaming every weather-related disaster on climate change can have negative consequences like amplifying climate anxiety and climate fatalism. Attributing disasters primarily to global warming can also divert attention from other, more easily fixable, local socioeconomic vulnerabilities that amplify those disasters.[26] For example, blaming climate change for flooding events can detract from a history of poor urban planning.

To make proper attribution, we need to determine scientifically if an extreme weather event, say event X occurring in 2022, was *significantly* affected by climate change. For unprecedented extreme events, we lack sufficient data to statistically analyze past events similar to X. Therefore, we have to use models. We use one or more climate models to generate two weather multiverses from 1850 to 2022: 1. A *factual weather multiverse* where greenhouse gases increased to their current concentrations from their 1850 pre-industrial values. This multiverse experiences global warming, as recorded in the historical data. 2. A *counter-factual weather multiverse* where we go back in time to 1850 and deliberately hold greenhouse gas concentrations fixed at their pre-industrial values. This multiverse experiences no global warming.

For each weather multiverse, for the year 2022, we count the number of times events similar to event X have occurred in the different universes. If the factual multiverse has many more events similar to X than the counter-factual one with the manipulated timeline, then we can blame global warming for its more frequent occurrence. The larger our multiverse populations and the better our climate models, the more accurately we can assign such blame. (Assigning blame for heat waves is easier than assigning blame for floods or droughts, because models are much better at predicting temperature changes than rainfall changes.)

2.4 Fate and free will in the multiverse

Climate prediction is extremely complex. It differs greatly from many simpler kinds of prediction that you may be familiar with from other disciplines. The pop culture notion of the multiverse allows us to illustrate this complexity, which is often glossed over by those predicting inevitable climate doom with certainty. Predictions with such fateful certainty can only happen in a simplified model universe that does not really belong in the multiverse of comprehensive models.

If you are a decision maker and someone presents you with predictions of future climate or assessments of climate risk, it is worth asking how they handled the three multiverse types. Hopefully, a better understanding of the climate multiverse can help you make more informed decisions in tackling the serious and urgent threat of climate change.

We don't have the superpower to choose which weather universe we will live in, because the dice roll of fate makes that choice. We have some power to trim the model multiverse

[25] Global warming above 1.5C could trigger 'multiple' tipping points (CarbonBrief.org)

[26] Damage Functions (or Why I am Mad at Climate Economists)](https://lpeproject.org/blog/damage-functions-economics-climate-science/)

with more research, but progress is not guaranteed.[27] We do have the superpower (i.e., free will) to control which emission multiverse we will live in. If we act to reduce emissions quickly, we will end up with a slightly warmer multiverse with fewer extreme heat waves and heavy rainfall events. If not, we will end up with a much warmer multiverse with many more (and stronger) such events.

2.5 Comments

Note: For updated comments, see the original blog post and the anouncement tweet.

- *R Saravanan*:
  Interesting blog post on The heatwave that never was
  Also discussed in this tweet thread
- *R Saravanan*:
  Another relevant paper: The importance of internal climate variability in climate impact projections, K. Schwarzwald and N. Lenssen, PNAS, 2022

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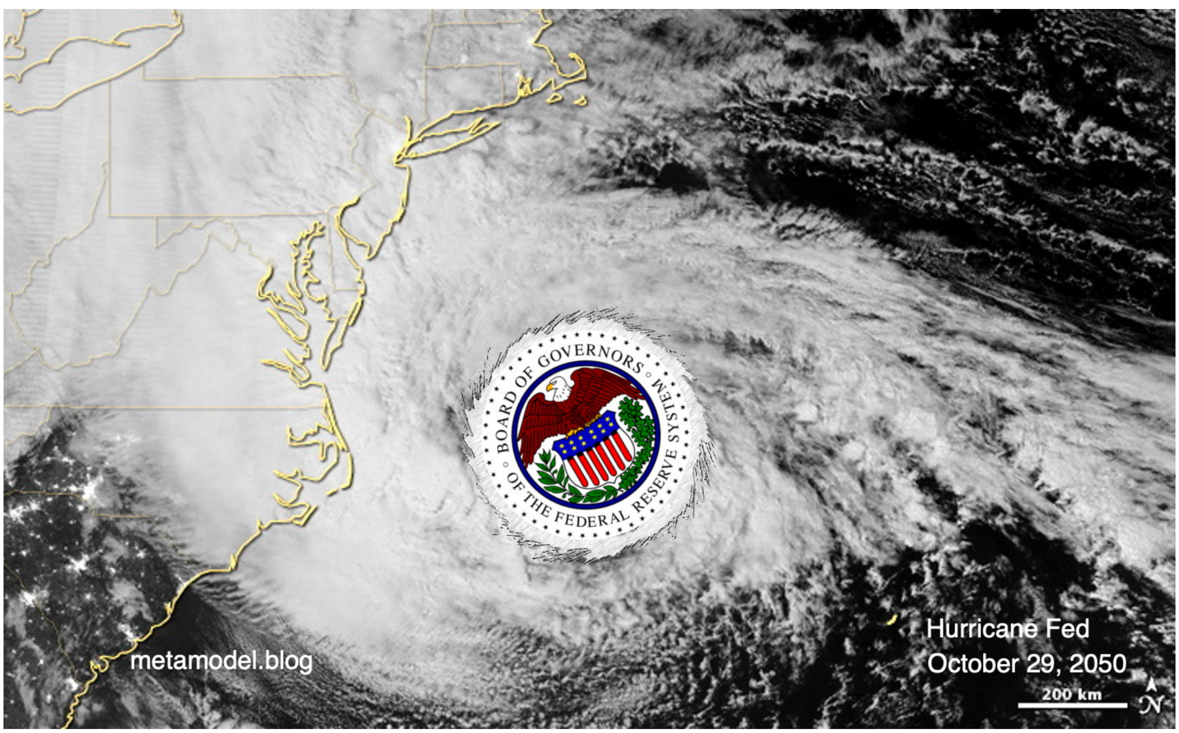
3 Hurricane Fed: The New Climate Stress Test for Banks

The Fed's new hurricane-based risk assessment is well-intentioned but poorly formulated. Since future hurricane probabilities are hard to predict, a simple storyline approach would have been better.

Metamodel.blog 2023-03-01



[27] Who's afraid of the Big Bad El Niño? (Metamodel.blog)

Recently, the US Federal Reserve ("Fed") issued guidance for a pilot exercise on how the six largest US banks should analyze their exposure to climate risk.[28] The Fed calls the study exploratory and says the results will have no capital implications. Nevertheless, this exercise is essentially a climate stress test—like the financial stress tests to check whether banks have enough capital to survive economic shocks. Other central banks around the world are taking similar steps. Climate change can lead to increased economic risk. Planning to deal with this risk, taking into account all the uncertainties, is prudent for the Fed and other central banks to advocate.

The Fed proposes a probabilistic assessment of the risk of an extreme hurricane event making landfall in the Northeast US in 2050 under two different carbon emission scenarios: a medium emission scenario, RCP4.5 and a high-emission scenario, known as RCP8.5. This sounds straightforward at the surface, but when you dig deeper the proposed assessment turns out to be quite complicated, involving many assumptions.

Predicting future climate and economic conditions requires using complicated models and scenarios. However, this doesn't mean that risk assessment needs to be framed in a convoluted fashion. When we ask bankers (and other lay people) to test for climate risk, it would be best provide guidance in the simplest terms possible. The Fed's risk estimation exercise fails the stress test of simplicity. As explained later in this article, a better way for banks to assess climate risk would be to use a simple "storyline approach" with a few well-defined assumptions about future climate change.

3.1 Problems with the Fed's guidance

In January 2023, the Fed issued instruction for the *Pilot Climate Scenario Analysis Exercise*[29], which asks the banks to assess physical climate risk in the following manner:

> [F]or the iterations of the common shock component, participants should estimate the impact of a hurricane event(s) within the Northeast region with the following characteristics:
>
> 1. Climate conditions broadly consistent with possible future climate conditions in 2050 as characterized by the SSP2-4.5 (or RCP 4.5) pathways with a 100-year return period loss...
> 2. Climate conditions broadly consistent with possible future climate conditions in 2050 as characterized by the SSP5-8.5 (or RCP 8.5) pathways with a 200-year return period loss...
> 3. Climate conditions broadly consistent with possible future climate conditions in 2050 as characterized by the SSP5-8.5 (or RCP 8.5) pathways with a 200-year return period loss...
>
> To estimate the impact of the hurricane event(s) in 2050 across the three iterations above, participants may need to make additional assumptions around the state of climate and the related chronic physical features in 2050, including, but not limited to, an increase in surface temperatures, sea level rise, and precipitation levels.

[28] Warning of unprecedented heatwaves as El Niño set to return in 2023 (The Guardian), Global heat waves show climate change and El Niño are a bad combo (NPR), The unusual factors behind the extraordinary heat across the southern US (Vox.com)

[29] Occam's (or Ockham's) razor is a principle attributed to the 14th century logician and Franciscan friar William of Ockham: *Pluralitas non est ponenda sine neccesitate*, or Entities should not be multiplied unnecessarily (UCR.edu)

Taken at face value, this sounds like the right approach. The Fed's reasoning appears to rest on the following chain of assumptions: *(i) risk assessments should be based on probabilities; (ii) extreme weather is expected to worsen with climate change; (iii) considering climate in a specific region rather than global average climate makes the assessment relevant to the US; (iv) decadal timescales are more important for financial risk than centennial timescales; and (v) different emission scenarios allow us to span the range of policy responses.*

Most people's intuition about climate change is based on the popular discourse on climate change, which often focuses on the global average temperature increasing over centuries. There is a clear separation of the global warming signal on centennial timescales as predicted by climate models for different emission scenarios—the globe will be much warmer under RCP8.5 than RCP4.5 by the year 2100. There is always random noise associated with unpredictable ("stochastic") variations associated with weather, but it is relatively small when temperature is averaged globally, because of cancellations amongst regional variations.[30]

However, nobody lives in "global-average-land"! While global warming thresholds of 1.5 (or 2.0)°C dominate newspaper headlines, what will affect your life is the warming in the region you live in. In the middle latitudes, the regional greenhouse gas warming signal remains roughly the same as the global warming signal, but the random noise will be a lot stronger, because the cancellation benefit of global averaging is lost. That makes it much harder to discern the regional warming signal. If we are interested in short-term warming (by year 2050, say), the warming signal becomes even weaker whereas the noise amplitude remains the same (Figure 1).

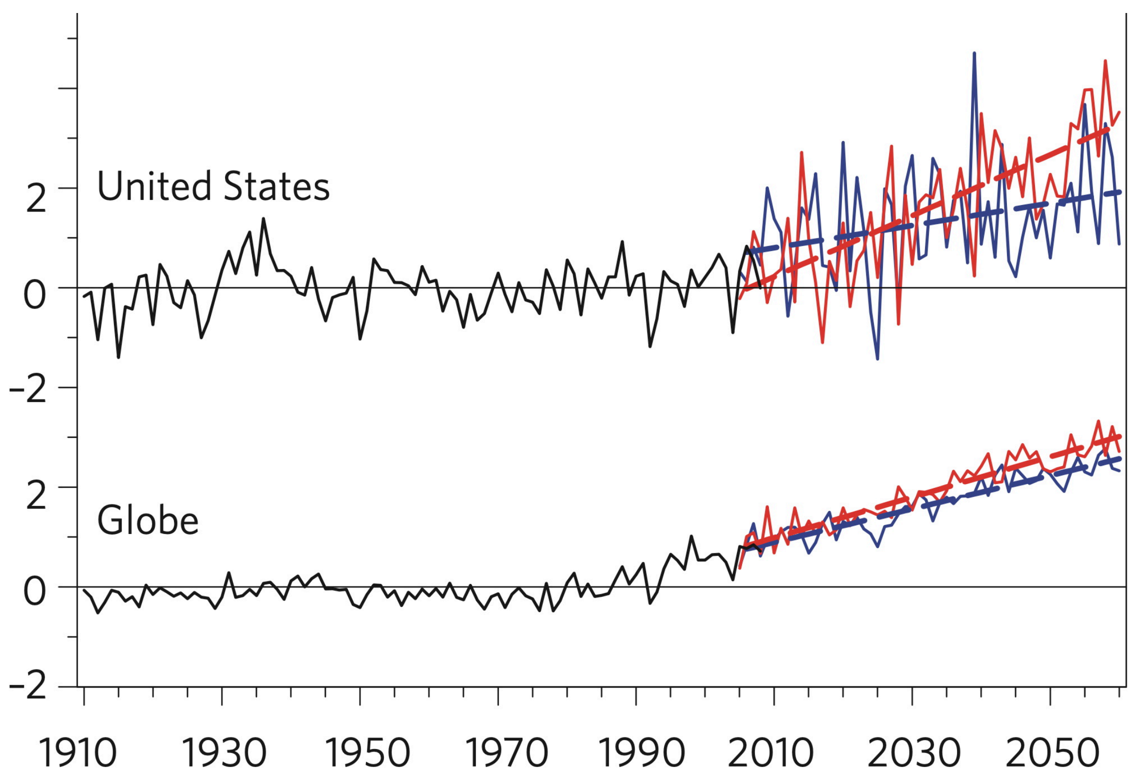


Figure 1 *Temperature change averaged over the globe and over the contiguous United*

[30]Ch.7, The Climate Demon: Past, Present, and Future of Climate Prediction (ClimateDemon.com)

States in observations until 2008 (black) and for a single emission scenario (A1B; similar to RCP6.0) until 2060, for the weather realization with the largest (red) and smallest (blue) future trends. The smaller the averaging region, the larger the random noise due to weather. [Adapted from Figure 2b of Deser et al., 2020][31]

The popular discourse on climate change also leaves the impression that just because we have models that predict future global warming, we can compute precise probabilities of all future extreme events like heat waves, heavy rainfall or hurricanes. Climate models simulate different phenomena with differing degrees of realism. Large-scale warming patterns and heat waves are simulated better than small-scale rainfall events. Uncertainties associated with different climate models make it hard to estimate precise future probabilities of regional extreme rainfall, for example (Figure 2).

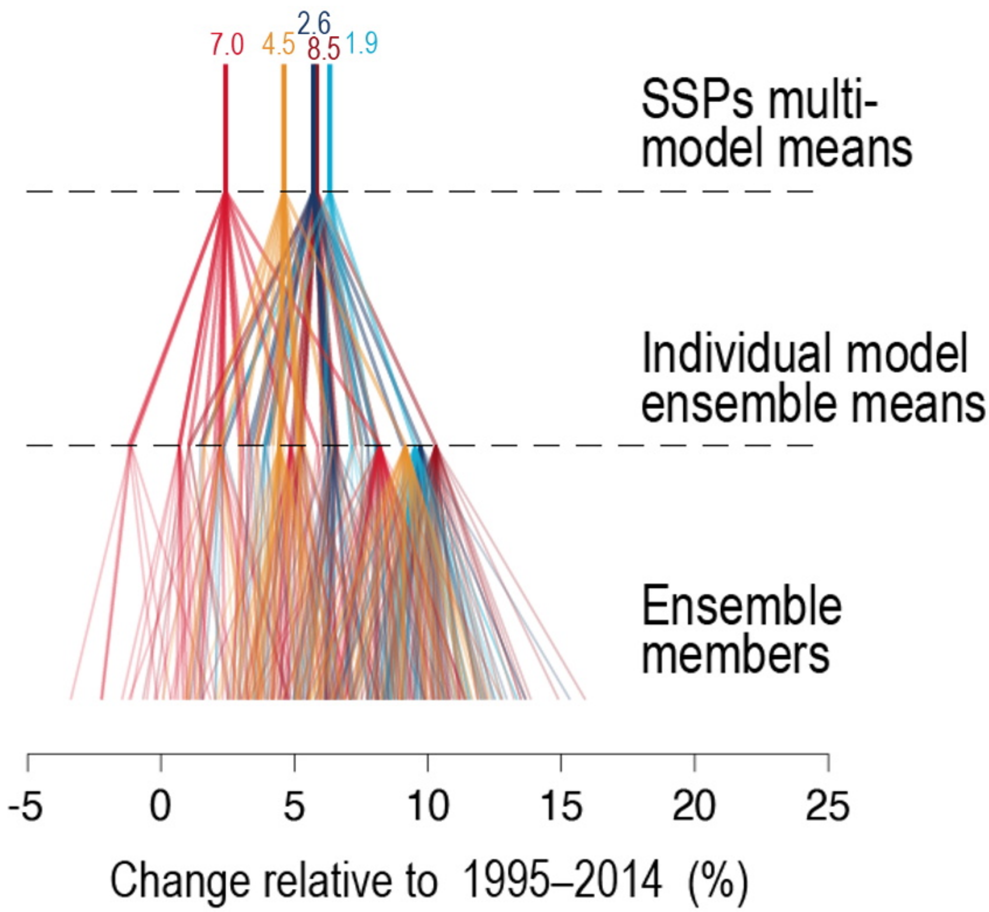


Figure 2 *Cascading uncertainties in IPCC model projections of East Asia summer (June-August) rainfall for multiple emission scenarios (SSP 1.9, 2.6, 4.5, 7.0, 8.5) for years 2041-2060. Top row shows average for each SSP; next row shows the average for individual models; bottom row shows the rainfall for each individual realization of weather in each model (representing the random variability). It is hard to distinguish*

[31] Is the weather actually becoming more extreme? (TED.com), The Butterfly Effect: Everything You Need to Know About This Powerful Mental Model (FS.blog)

between emission scenarios 4.5 and 8.5 when looking at the spread of simulated rainfall in the year 2050. Interestingly, the lowest emission scenario, 1.9, shows the largest rainfall changes in the near term due to the effect of aerosols in that scenario. [Adapted from Figure 1.15 of IPCC AR6 WG1 report][32]

With the above caveats in mind, we focus on weak links in the chain of assumptions (i)—(v) that underlie Fed's guidance.

(i) *Risk assessments should be based on probabilities*. By specifying numeric probabilities (e.g., 100-year return period loss), the Fed aims to make the risk assessment precise. That would work if we knew the precise probabilities of hurricanes making landfall in the Northeast US in the year 2050. But we don't. Our current global climate models have too coarse spatial resolution to estimate the precise probability of future hurricane landfalling events. The current horizontal grid of climate models is at best about 50kmX50km—not enough to resolve the eyewall of a hurricane. Making additional assumptions and using simpler/regional models, we can come up with numbers for future hurricane probabilities, but the answers will be sensitive to the assumptions.[33]

(ii) *Extreme weather is expected to worsen with climate change*. This statement is generally true, but the devil is in the details. Large-scale weather extremes like heat waves will uniformly get worse but the picture is more complicated for hurricanes because they involve small-scale moist processes. According to our current scientific understanding, the strength of hurricanes and the associated rainfall are expected to increase but their total number may actually decrease (Figure 3). The strongest hurricanes are expected to get even stronger and may increase in number. If the total number of hurricanes does not increase, it implies that weaker hurricanes, such as Category 1 or 2, will decrease in number.

[32] When the Butterfly Effect Took Flight (MIT Technology Review)
[33] Anatomy of a heat wave (theclimatebrink.substack.com)

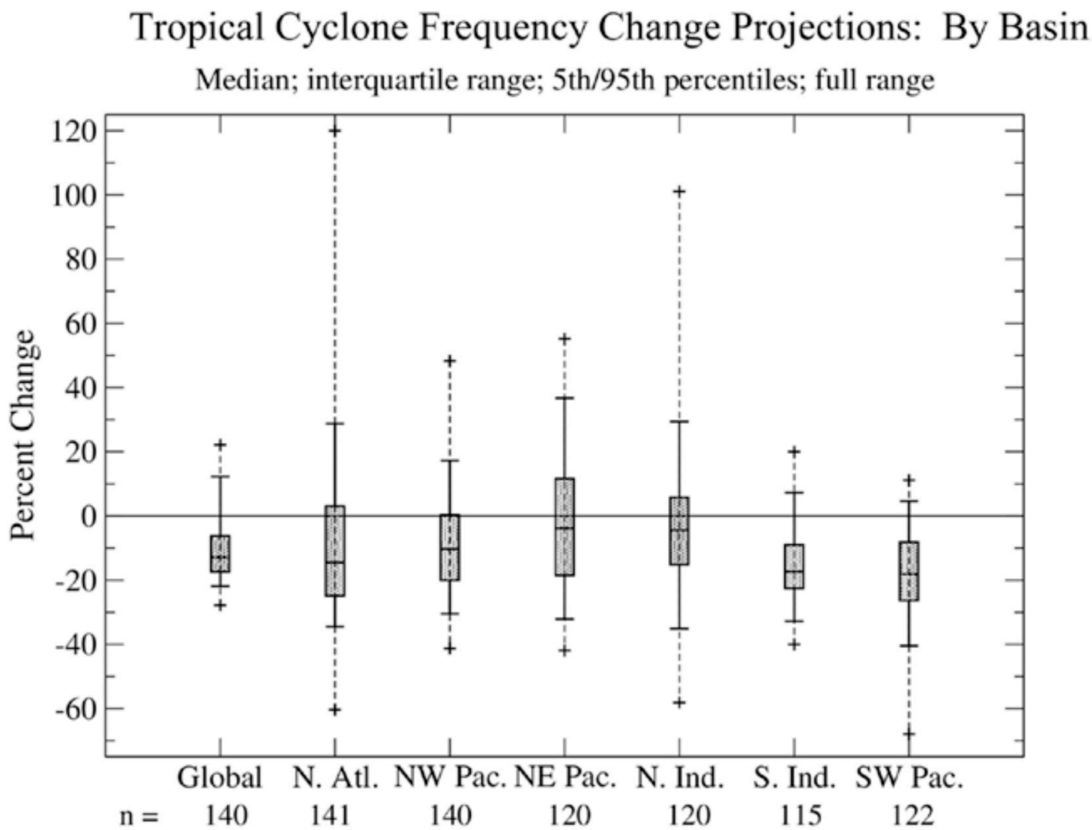


Figure 3 *Projected changes in the frequency of tropical cyclones (known as hurricanes in the North Atlantic) for each ocean basin for 2°C of additional global warming compared to current conditions. Hurricane frequency in the North Atlantic is projected to decline about 15% on the average, but the uncertainty range is huge!* [Adapted from Fig. 1b of Knutson et al., 2020][34]

The Fed's choice to focus on an extreme hurricane affecting the Northeast US is presumably motivated by an actual natural disaster, Hurricane Sandy, that wreaked havoc in that region in October 2012, killing hundreds of people and inflicting many tens of billions of dollars in damage.[35] But Sandy was not very strong, as hurricanes go; it barely reached a peak intensity of Category 3 and made landfall as a Category 1 storm. Bankers may be surprised to learn that climate change might actually make weak storms like Sandy rarer in the future.

Of course, a stronger hurricane than Sandy could impact the Northeast in the near future. Such a rare event could happen purely by chance, even in the absence of additional warming between now and 2050. Future global warming could be responsible for amplifying the storm, but the distinction between different emission scenarios may not be very discernible by the year 2050.

(iii) *Considering climate in a specific region rather than global average climate makes*

[34] Assessment of Historic and Future Trends of Extreme Weather in Texas, 1900- 2036, 2021 Update. Document OSC-202101 (J Nielsen-Gammon et al., 2021:, Office of the State Climatologist, Texas A&M University)
[35] Strange weather in the multiverse of climate (Metamodel.blog)

the assessment relevant to the US. Yes, but the regional focus also greatly increases the strength of random (stochastic) noise as discussed earlier. To probabilistically assess regional climate change for a small area like the Northeast US, we would need a large ensemble of climate model simulations to quantify the random noise[36] — something the Fed's guidance fails to note.

(iv) *Decadal timescales are more relevant for financial risk than centennial timescales*. True, but focusing on shorter timescales means the global warming will be weaker and less sensitive to the scenario being considered. Coupled with the much larger amplitude of random variability, as noted in the (iii) discussion, there may be no point in trying to distinguish between the signals of RCP8.5 vs. RCP4.5 by 2050, as the Fed recommends.

(v) *Different emission scenarios allow us to span the range of policy responses*. Yes, but it would become a moot issue with the lower signal-to-noise ratio, as noted in the discussion of points (iii) and (iv) above.

The Fed's guidance may sound well-defined and numerically precise on the surface, but it isn't quite so. The numerical precision of the specified return period loss becomes irrelevant if our estimates of the probability of the physical hazard, i.e., future landfalling hurricanes, are themselves imprecise. Since banks are free to make numerous additional assumptions needed to estimate the physical hazard, the guidance is poorly formulated. Even seemingly small errors in these assumptions can lead to big errors in the estimation of tail risk of the physical hazard.[37] The uncertainties associated with the assumptions can be lost in translation, leading to faux precision in the final risk assessment.

3.2 The super-Sandy storyline

Since climate risk is real and important, is there is a better way to assess its impact on the banking sector? One that does not involve hard-to-compute probabilities and a multitude of assumptions? Instead of hiring consultants to make many small assumptions involving a cascade of models that we can't keep track of, can't we just make a few big assumptions? Wouldn't it be more transparent if we are upfront about the uncertainties?

An alternative, and simpler, way to frame the risk assessment is to start with a known extreme event, say Hurricane Sandy that affected the Northeast US in 2012, and ask how a stronger version of this storm occurring in the near future would affect bank finances. Such an approach, often referred to as a "storyline", is better suited to describing future high-impact low-likelihood events whose probabilities are hard to quantify.[38]

Scientific research shows that global warming amplifies the water cycle, meaning that extreme storms like Sandy can become more intense as the atmosphere becomes moister. One can assess the financial risks of a stronger "super-Sandy" hurricane, say 10% stronger than Sandy, making landfall in the Northeast US. Such an assessment should also include estimates of higher sea-levels by the year 2050, which would amplify the coastal impacts.

[36] Who's afraid of the Big Bad El Niño? (Metamodel.blog)

[37] "Widespread observed and projected increases in the intensity and frequency of hot extremes, together with decreases in the intensity and frequency of cold extremes, are consistent with global and regional warming." p.1523, IPCC AR6 WG1 Report

[38] The Texas Power Grid Failure Is a Climate Change Cautionary Tale (TIME.com)

The storyline framing possesses several advantages. It sidesteps the contentious issue of whether the high-emission RCP8.5 scenario—required by the Fed—is even a plausible future.[39] According to the latest international climate assessment from the IPCC, recent trends in the energy sector mean that the likelihood of the RCP8.5 scenario is low. The storyline framing focuses on the narrower question of whether a super-Sandy storm impacting the Northeast US by 2050 is a plausible event. The combination of climate change and random variability can make such an event plausible. (If need be, we can consider different plausible strengths of super-Sandy to span the range of physical risk.)

The current Fed proposal allows the use of *a la carte* assumptions to assess climate risk. Banks may end up making different modeling assumptions. A smorgasbord of assumptions will mean that comparing risk assessments from different banks will be like comparing apples to oranges. A simpler alternative is to assess financial impacts using a well-defined storyline with fewer assumptions. That can provide a clearer picture of the climate risk faced by banks.

Keep it simple, Fed!

(*Top image shows a NASA satellite view of Hurricane Sandy approaching the Northeast US on October 29, 2012, with the Federal Reserve logo in the eye of the storm.*)

3.3 Comments

Note: For updated comments, see the original blog post and the anouncement tweet.

- *Stephen Jewson*:
  Hello, I'd quite like to respond to this blog, in the spirit of debate, from the point of view of a climate risk modeller. What's the best way for me to do that? I'm not sure this little box is quite the best way to do that. What do you suggest? Can I write an article that you could post on your blog?
  - *R Saravanan*:
    Sure, you are welcome to post a guest «rebuttal» article on this blog.
- *Stephen Jewson*:
  But long story short, multiple models already exist that can be used to answer the Fed's questions. They've been built by climate scientists like you and me, and, by and large, deal with all the issues you raise in your post, plus a whole load of other relevant issues. They avoid over-precision by propagating and communicating uncertainty and allowing sensitivity tests i.e., in the normal way.
  Many folk in the financial industry have these models at their fingertips already. Their answers to the Fed's questions, which they could calculate any time they want, would be based on simulations of 1000s of possible storms that might hit NY, including their wind, flood and surge damage, all adjusted for distributions of possible climate change. Boiling all of that down to just 1 event, when they already have the whole distribution, would throw away an enormous amount of information about risk. It'd be a bit like reducing all of climate modelling to one ensemble member from one climate model.
  Are the models perfect? Of course not. They are a work in progress, just like everything else. Even after 50 years (the first journal paper on probabilistic hurricane risk modelling was published in 1972) it's a rapidly evolving field, especially because of climate change. Different models by different groups have different strengths and weaknesses. We can pick holes here and there, and propose improvements, and more transparency would be good. But for questions like the

[39] Global warming above 1.5C could trigger 'multiple' tipping points (CarbonBrief.org)

questions the Fed are asking, the current models do a reasonable job (I would say). 2100 would be much harder. Tornado-hail would be much harder .
If there are particular technical points you are interested in, let me know. E.g., you mention the Knutson et al (2020) paper. If you're interested in how the results from that paper are post-processed for use in risk models, and propagated thru into loss estimates, while still preserving the uncertainty, I can send you links to several peer-reviewed papers on that.
s

- *R Saravanan*:
  Simulation of hurricanes in global climate models is still highly «dodgy», to borrow a British expression. The quantitative results are research-grade, but not yet application grade (and may not be for a while). A new generation of global models could yield different research results, invalidating any prior application of the results to risk assessment. (The storyline approach avoids this built-in obsolescence by making the uncertainties explicit, not hidden.) I know that there are models that simulate 1000s of possible storms. But the answers they provide vary with the assumptions used to build them. End users are often not aware of this and end up treating the results with more precision than is deserved. Yes, we can propagate uncertainties, but what is the point of propagating huge uncertainties of the kind shown in Knutson et al. 2020/Fig. 3 of this post? The numbers may well be different in future peer-reviewed papers Knutson et al., 2024. or 2028. Peer-reviewed means that the published model results are the best research estimates at the time of publication. It does not guarantee stationarity of the statistics that is needed for true risk estimation. That's because the quantified uncertainty does not consider the unquantified structural model uncertainty. Actually, I like it that the Fed chose to focus on a single event, rather than 1000s of events simulated by assumptive models, where different groups may make different assumptions. The problem is that the Fed chose to define that 1 event using a «return loss period» which adds the damage function uncertainty to the hurricane probability estimation uncertainty. You argue that by focusing on 1 event, we are throwing out information about risk. I would argue that the information thrown is not actuarial risk, but guesstimates.
  Ultimately, I think our disagreement is philosophical. Is precise (actuarial) risk assessment possible for poorly simulated phenomena like hurricanes in 2050? Conventional risk assessment assumes it is possible, storylines don't.
  * *Stephen Jewson*:
    One thing you and I totally agree on: that over-interpretation of approximate and uncertain results is a bad thing, whatever the topic.
    I see risk assessments as being more like weather forecasts: they start with low signal and large uncertainty, and then gradually improve. So I'm not sure I'd ever use words like "precise" or "true risk". I would say that risk assessments are just what we can deduce, right now, based on the information available. More subjective Bayesian than objective frequentist. The best way to avoid a shock, with both, is to start watching them early on, and track them as they develop. We start weather forecasts as soon as there's a signal…and it seems that there's a signal in the climate projections for 2050, albeit small and uncertain.
    I wonder what you'd think about hurricane risk estimates for 2023: they are also extremely uncertain…not that much less uncertain than the estimates for 2050, in fact, if you factor in all the sources of uncertainty.

But we've got to make quantitative risk assessments, because people need them for quantitative decisions.
Apart from everything else, we've learnt a huge amount about hurricanes and climate change by making these risk assessments. Not about hurricane physics, but about how to count and measure hurricanes, what information we need from climate models, and how to process it. It took me 2 years to figure out how to extract the right information from the Knutson et al. projections, and there were some big surprises. Next time (Knutson et al. (2024), as you say) hopefully it'll take a couple of weeks, given that learning. The sooner we start providing risk assessments to users, the sooner they can start their own learning curve.
Makes me laugh that we are citing Tom's paper that he hasn't even written yet. Should we tell him? Does that count as a proper citation? Watch out or you might start a citogenesis process.
s

∗ *R Saravanan*:
This has been a useful discussion. Thanks for the LinkedIn post with the quick (and useful) hurricane analysis. I would use that analysis, but in a somewhat different way. One thing I wasn't very specific about in my blog post is how to construct the storyline. I simply threw out a round number like 10% stronger for super-Sandy. One could consider a range of super-Sandy storms, say 5%, 10%, and 15% stronger, perhaps, to span a range. The way to pick the range would be to consider analyses like yours and others (but purely for physical risk) to choose some plausible numbers. Once we pick the storyline, we don't need to go back to conventional risk analysis. Knutson et al (2024/2028) might just move the needle of plausibility in the storyline dial.
The problem with the Fed's guidance is that it lets banks pick different ways to estimate risk and conflates physical risk with damages. As you note in your comment, subjective Bayesian estimates could yield different numbers for risk. Each bank may effectively be using a different storyline hidden in their methodology, making it difficult to compare the final stress test results.
There's a big difference between hurricane risk analysis for 2023 and 2050. We know what the regional background state will be in 2023, but there is much greater uncertainty about the background state for 2050. Regional climate prediction is hard. This will greatly amplify the uncertainty. Different subjective analyses may give very different results. If your results for 2050 differ greatly from that of company X or Y, which one should we trust? On what basis?

∗ *Stephen Jewson*:
Don't underestimate the uncertainty around risk analysis for 2023 though. We may know the climate state, but the epistemic uncertainty around any estimate of the expected number of major storms making landfall, even given the climate state, is huge, especially regionally. Even for 2050, that uncertainty may dominate climate change uncertainty (I have a paper about that but it's not published yet...there's a point in time at which those two sources of uncertainty cross over and climate change overtakes...question is, when is it). So company X and company Y are already very different for 2023, not to mention company Z. To decide which one to trust, all you can do is look at what they are doing, look at

their assumptions, make your own assessment, and then apply weights. If you are not confident in making an assessment, you could run an expert elicitation for the weights. It's not completely objective, that's for sure. There's a conference in London today on this stuff, and I need to go put my suit on.

- *R Saravanan*:
  Found a LinkedIn post discussing similar issues. It has some additional references to recent activity on storylines and narratives.
  Why climate models struggle with acute physical risks
  https://www.manifestclimate.com/blog/why-clim…
- *R Saravanan*:
  Another relevant reference: Acute climate risks in the financial system: examining the utility of climate model projections
  https://iopscience.iop.org/article/10.1088/2752-5295/ac856f#references
  We strongly encourage a review of existing top-down approaches before they develop into de facto standards and note that existing approaches that use a 'bottom-up' strategy (e.g. catastrophe modelling and storylines) are more likely to enable a robust assessment of material risk.
- *Stephen Jewson*:
  Just to prove that hurricane risk modelling is a real thing, I spent the morning actually running some numbers for NY hurricane risk in 2050. I've posted the results on my Linkedin page, along with all the scientific journal citations to the methodologies I'm using. Comments welcome.
  - *R Saravanan*:
    Link to Steve Jewson's post: https://www.linkedin.com/posts/steve-jewson-p…

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4 Who's afraid of the Big Bad El Niño?

El Niño is not Global Warming (except in Global-average Land). They have different physical causes and different spatial impacts, even though, arithmetically, they both raise global-average temperature.

Metamodel.blog 2023-06-16

WMO's afraid of the Big Bad El Niño.

The World Meteorological Organization (WMO) says there's now a 66% chance that we will breach the 1.5°C global warming threshold between now and 2027, as reported in a recent BBC article.[40] This increased probability is being blamed on the heat expected from an imminent El Niño. While noting any such breach will be temporary, the article goes on to say that "breaking the limit even for just one year is a worrying sign that warming is accelerating and not slowing down." A spate of media reports now predicts that the impending Big Bad El Niño will push global warming into "uncharted territory".[41]

El Niño, a phenomenon first observed centuries ago by Peruvian fishermen, refers to a sporadic warming of the tropical Pacific Ocean that occurs every 3-7 years.[42] These waters, usually cold and teeming with nutrients, would warm considerably, decimating fish populations. The phenomenon typically occurred around December or January, hence its name, El Niño—Spanish for "the boy child", a reference to Christ.

El Niño's impact, propagated by atmospheric waves known as teleconnections, extends to regions far removed from the tropical Pacific.[43] For instance, it intensifies winter rainfall in California while potentially inducing drought in Australia. Recent warming in the Pacific Ocean has prompted the US weather agency to declare an official El Niño event

[40] Warning of unprecedented heatwaves as El Niño set to return in 2023 (The Guardian), Global heat waves show climate change and El Niño are a bad combo (NPR), The unusual factors behind the extraordinary heat across the southern US (Vox.com)

[41] Occam's (or Ockham's) razor is a principle attributed to the 14th century logician and Franciscan friar William of Ockham: *Pluralitas non est ponenda sine neccesitate*, or Entities should not be multiplied unnecessarily (UCR.edu)

[42] Ch.7, The Climate Demon: Past, Present, and Future of Climate Prediction (ClimateDemon.com)

[43] Is the weather actually becoming more extreme? (TED.com), The Butterfly Effect: Everything You Need to Know About This Powerful Mental Model (FS.blog)

for 2023.[44] When the tropical Pacific warms, it invariably raises the global-average temperature, because the Pacific covers such a large fraction of the globe. This basic arithmetic relationship has fueled a flurry of articles linking El Niño with global warming, prompting questions like:[45]

- *Is the coming 2023 El Niño going to accelerate global warming?*
- *Will El Niño trigger severe heatwaves in Europe or the U.S.?*
- *Can El Niño fueled global warming push climate over a tipping point?*

The short answer to these questions is a no, because El Niño is a quasi-cyclical natural phenomenon whose physical cause and spatial impacts are distinctly different from human-induced global warming. Why then does the media overtly or subtly suggest otherwise? Because they are conflating the symptom with the disease. A viral sinus infection and a bacterial lung infection and can both raise body temperature to fever levels, but they affect the body differently. Similarly, El Niño and global warming have different spatial patterns of impacts, even as they share the symptom of rising global-average temperature.

We should be afraid of El Niño—where it's both big *and* bad. We fear the big bad wolf, but we are not afraid of a small bad chihuahua—and we all love big friendly dogs. El Niño is all the above. Whether you should be afraid of El Niño depends upon where you live, the time of year, and what climate variable you are interested in. For spring rainfall in Northeast Brazil, El Niño is a big bad wolf but for summer temperature in Texas, it's more of a chihuahua. In some places, El Niño can be a friendly dog, countering global warming by cooling summer temperatures or reducing hurricane activity.[46] (*You can check if El Niño is going to be a wolf or a chihuahua in your town using two interactive plots in this article: Figure 3 and Figure 7.*)

Global warming is an urgent problem that we are dealing with through mitigation and adaptation. We have sort of adapted to El Niño, because it is a natural phenomenon. Will the coming El Niño take us into uncharted territory? To answer that, we have to explore the charts we've got. We start in *Global-average Land*, undoubtedly the best charted and most popular climate destination. Then we travel to less-explored *Local-average Lands* and end by explaining how El Niño is counterintuitive in many ways.

When preparing this article, despite a ton of published material on El Niño over several decades, finding graphics that directly compared El Niño and global warming in a relevant way wasn't easy. So, I wrote code to generate all the figures in this article (except for the schematic). The code is available as a Python notebook on Google Colaboratory.[47] *A better set of clickable plots of El Niño impacts for is available on a separate web page.*[48]

[44] When the Butterfly Effect Took Flight (MIT Technology Review)
[45] Anatomy of a heat wave (theclimatebrink.substack.com)
[46] Assessment of Historic and Future Trends of Extreme Weather in Texas, 1900- 2036, 2021 Update. Document OSC-202101 (J Nielsen-Gammon et al., 2021:, Office of the State Climatologist, Texas A&M University)
[47] Strange weather in the multiverse of climate (Metamodel.blog)
[48] Who's afraid of the Big Bad El Niño? (Metamodel.blog)

4.1 Simple narratives in Global-average Land

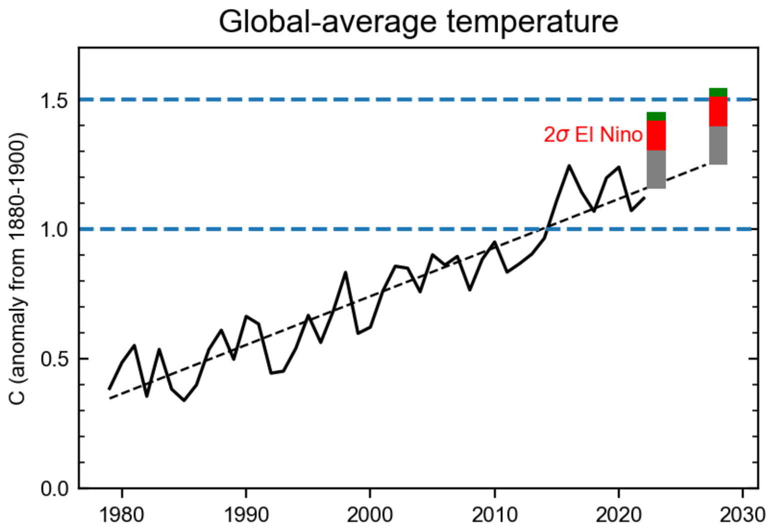

Figure 1 *Global-average temperature during 1979-2022 from the NASA GISTEMP4 dataset. The dashed line shows the linear trend. For 2023 and 2028, the red bar estimates the impact of a strong (2σ) El Niño event on the global average, derived through linear regression. The grey bar represents an estimate of measurement error, because GISTEMP estimates could be approximately 0.15°C lower than some other estimates. The green bar represents an estimate of the warming effect of Hunga Tonga eruption (0.035°C).*[49]

Global-average temperature has become the totemic[50] metric of global warming.[51] The complex phenomenon of long-term regional warming driven by carbon emissions is often simplified to narratives focused on global-average temperature. This simplification unfolds in *global-average land*, where discussions about warming thresholds, tipping points, and geoengineering frequently take place. In this simplified world, El Niño is no different from short-term global warming. That explains why media coverage fixates on how the 2023 El Niño might raise global-average temperatures, breaching the 1.5°C threshold (Figure 1).

However, global-average land is like Disney's Magic Kingdom—a refuge from the complexity of reality where many scientists, economists, reporters and policymakers like to hang out.[52] Real people, though, live in cities, counties, and countries, where it matters how hot (or cool) it's going to be locally, not in some abstract global-average.[53] Important details of climate change, such as regional warming and drying patterns, are absent in global-average land. The globe is not heating uniformly; it's warming faster near the poles but slower in the tropics (Figure 2). In fact, some parts of the ocean have been getting slightly cooler over the past 40 years!

[49]"Widespread observed and projected increases in the intensity and frequency of hot extremes, together with decreases in the intensity and frequency of cold extremes, are consistent with global and regional warming." p.1523, IPCC AR6 WG1 Report

[50]The Texas Power Grid Failure Is a Climate Change Cautionary Tale (TIME.com)

[51]Global warming above 1.5C could trigger 'multiple' tipping points (CarbonBrief.org)

[52]Damage Functions (or Why I am Mad at Climate Economists)](https://lpeproject.org/blog/damage-functions-economics-climate-science/)

[53]"[Global Mean Temperature] provides little insight on how acute risks likely material to the financial sector ('material extremes') will change at a city-scale." Acute climate risks in the financial system: examining the utility of climate model projections (A. J. Pitman et al., 2022; Environmental Research: Climate)

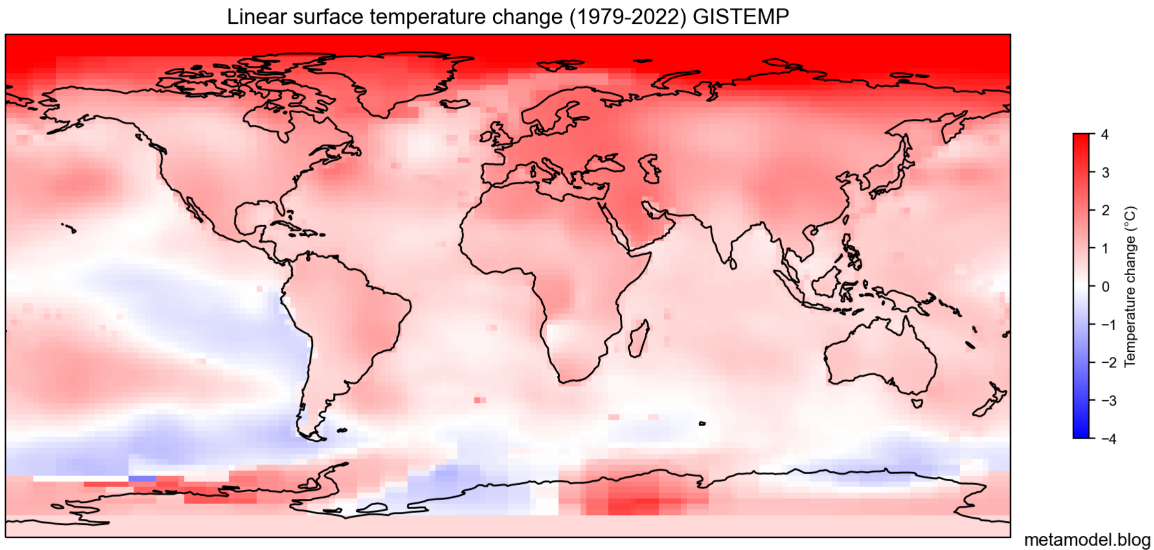

Figure 1: Linear surface temperature change between 1979 and 2022

Figure 2 *Linear change in surface temperature between 1979-2022.* NASA GISTEMP4 data

Figure 3 *Regression of seasonal surface temperature against the NINO3.4 El Niño index (multiplied by 2 to capture the impact of a strong El Niño). Summer regression is presented for each hemisphere: Jun-Aug for northern and Dec-Feb for southern. Green circles denote time series locations for Figure 5. Note that the regression map isn't masked for lack of statistical significance in order to the highlight the estimated impact of El Niño. The actual impact may be weaker than what is shown. Also, even statistically significant correlations may not be practically relevant if they are low.* [***NOTE: This figure is interactive.*** *Click anywhere on the globe to compare the local time series of seasonal temperature to the global warming trend and the regressed signal of 2σ El Niño to visually assess the statistical and practical significance. Alternatively, enter latitude, longitude values in the box and use button+drop-down to generate overlay/inline plot. Click on any blank area of plot to make it go away.*]

The much-discussed 1.5°C warming threshold is also a concept that belongs to global-average land. This threshold was originally proposed to deal with a more gradual but inexorable aspect of climate change—sea level rise.[54] Island nations were afraid that the Paris Agreement's 2.0°C warming target wasn't aggressive enough to stop sea-level rise, as sea level would continue to rise even after we stopped all emissions.[55] So they pushed for the tougher 1.5°C warming target. The talk of a planetary boundary or climate tipping point at 1.5°C warming came later—what was just a convenient round number target to start with became a physical threshold that should not be crossed.[56]

Different ways of measuring surface temperature give different values for current global warming, sometimes as much as 0.1-0.2°C different. We don't have good temperature data from before the industrial age, so we can't say precisely how much warmer it

[54] Addicted to global mean temperature (Isaac Held's Blog; gfdl.noaa.gov)
[55] 1.5°C: where the target came from – and why we're losing sight of its importance (TheConversation.com)
[56] Why are the (climate) numbers so round? (Metamodel.blog)

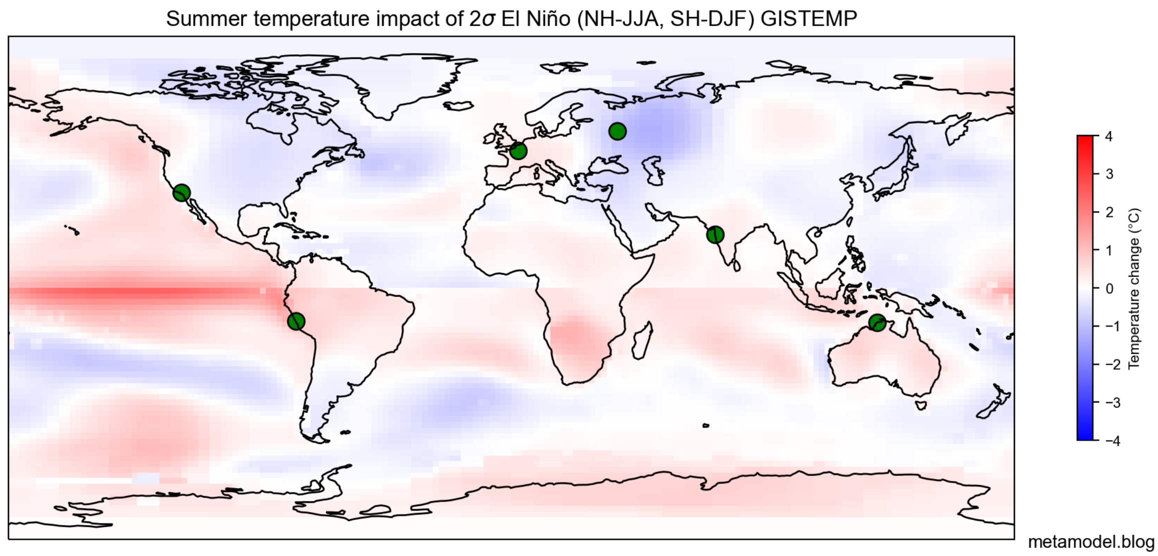

Figure 2: GISTEMP_DJA_regr

is now.[57] So, even if there were a physical threshold that should not be crossed, we couldn't tell if it's at 1.4, 1.5, 1.6°C. WMO's recent projection of a 66% probability of El Niño pushing beyond use over the 1.5°C threshold would be quite different if we used a different temperature dataset (Figure 1).

Instead of worrying about poorly defined global tipping points or fuzzy thresholds,[58] we should be focused on the nonlinearity of local damage functions, or how impacts of climate change accelerate as local temperatures increase. Going from 1.5 to 1.7°C will typically cause more than twice as much harm as going from 1.5 to 1.6°C, because we are adapted to our current climate. *Every tenth of a degree hurts, but the later tenths hurt even more!*

Getting back to El Niño: Talking about how it raises the global-average temperature misses the point that El Niño affects different regions in different ways. We look at how summer temperatures change with El Niño in both hemispheres, to understand how it may affect heatwaves (Figure 3). We see that the pattern of El Niño's impact differs greatly from that of long-term warming—it exhibits less spatial consistency, reveals extensive cooling areas, and is strongest in the tropics. Its influence spreads from the tropical Pacific through waves that can alternately warm and cool as they propagate. Global warming is more of a local thermodynamic effect that warms almost everywhere.

In practical terms, if you live in the southern US and hear a forecast that global-average temperature will rise by 0.1°C due to El Niño, should you brace yourself for more heatwaves? Not really. El Niño typically slightly cools the southern US during summer. While some places will indeed experience hotter summers (and more heatwaves) due to El Niño, many places won't experience any notable warming attributable to El Niño. That's different from global warming, which makes summer heatwaves worse across North America and Europe. That said, El Niño does ramp up heatwaves in some tropical areas and a few spots in the southern hemisphere, such as southern Africa and

[57] Will global temperatures exceed 1.5C in 2024? (Substack)
[58] Mechanisms and Impacts of Earth System Tipping Elements (S. Wang et al., 2023; Reviews of Geophysics)

eastern Australia.

4.2 Charting signal vs. noise in Local-average Lands

Often, El Niño discussions centering on its spatial pattern default to schematic maps (Figure 4). These maps tell us the sign of the seasonal impacts, but not the relative strengths of those impacts compared to natural variability or global warming. The maps don't tell us if it is a 5% effect or a 50% effect, for example.

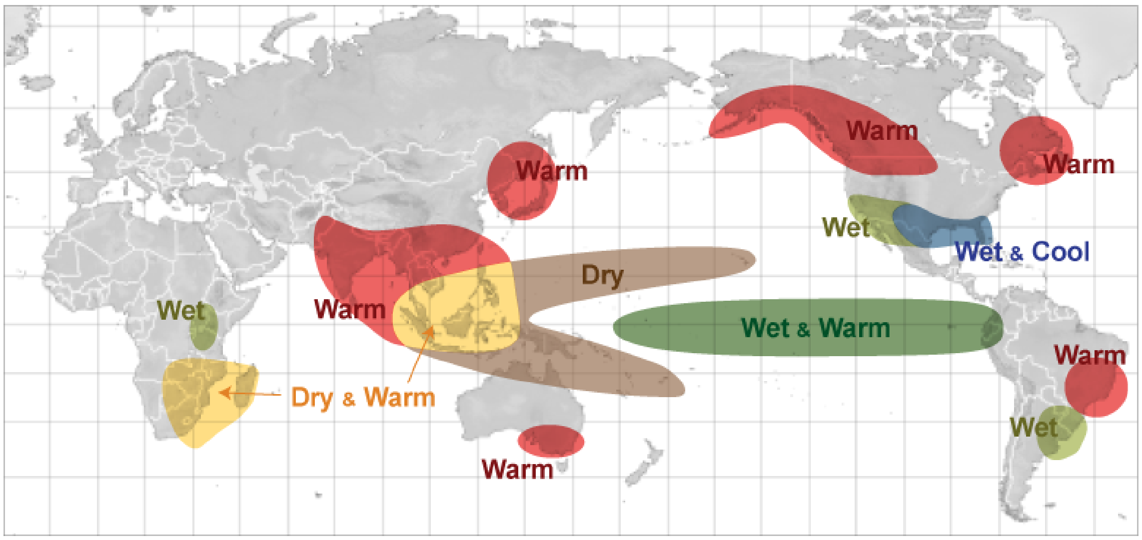

Figure 4 *How El Niño affects weather during December to February. [Image from weather.gov]*

We need more than schematic maps to understand how global warming affects different geographical regions, and how that differs from El Niño. We need to look at how local temperature changes over time (Figure 5). The global warming signal dominates the global-average time series, but it is less conspicuous at regional scales. Natural fluctuations in year-to-year local temperature play a bigger role regionally. We can also see how the tropics warm more slowly, and the polar regions warm much faster.

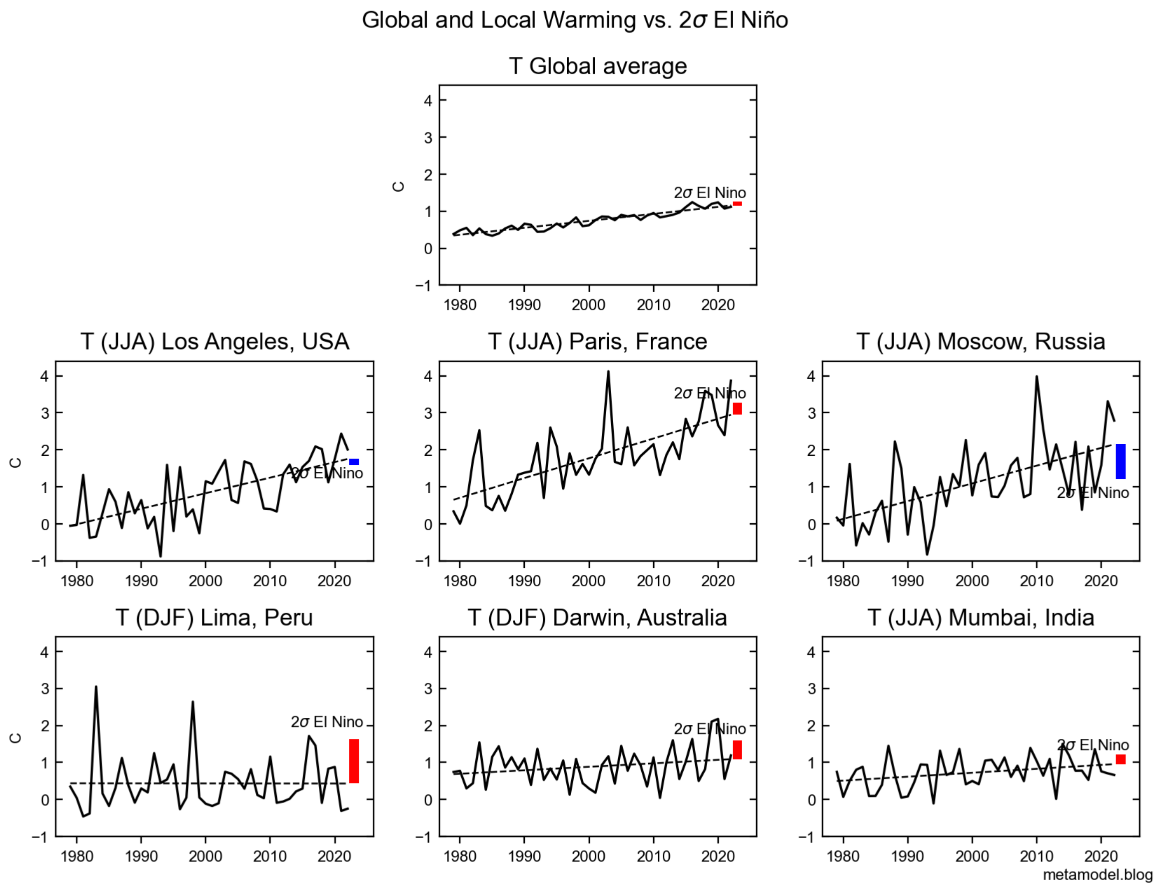

Figure 5 *The top panel reproduces the global-average temperature time series shown in Figure 1, but with a larger range for the Y-axis. Lower panels show local temperature changes during summer at locations marked by green circles in Figure 3. The dashed line displays the fitted linear trend. The red/blue bars denote the warming/cooling impact of a strong (2σ) El Niño, as estimated by linear regression. [Click on Figure 3 to make your own plot for your favorite location.]*

El Niño is considered the 800-pound gorilla of seasonal prediction,[59] but even a strong (2σ) event does not always stand out against the backdrop of natural variability and global warming. The impact of a strong El Niño on summer temperatures is significant in some tropical regions, but usually quite mild outside the tropics (see also Figure 3). In Lima, for instance, heatwaves would not be attributable to global warming, as there is no discernible long-term temperature trend. However, they can be attributed to El Niño. On the other hand, in Los Angeles, it's the other way around: there's long-term local warming, but El Niño has only a weak cooling effect during summer.

[59] Slow slosh of warm water across Pacific hints El Niño is brewing (Climate.gov)

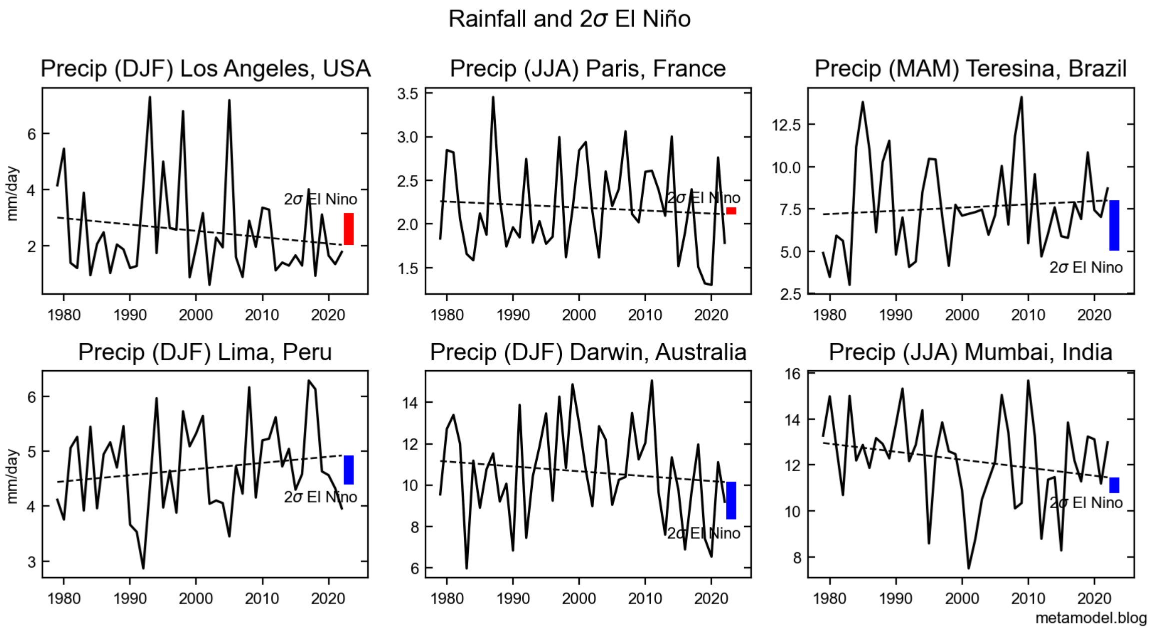

Figure 6 *Local seasonal rainfall between 1979 and 2022 in selected cities marked as white circles in Figure 7. Dashed line represents the fitted linear trend. Red/blue bars show the moistening/drying impact of a strong (2σ) El Niño, as estimated by linear regression. Note: The Y-range varies for each location. [Click on Figure 7 to make your own plot for your favorite location.]*

Besides temperature, El Niño influences rainfall patterns around the globe (Figure 6). However, rainfall is naturally more variable than temperature. This means the global warming signal is weaker and more regionally disparate. The El Niño influence on rainfall is largely confined to the tropics and the subtropics, but with some exceptions like California and the southern US (Figure 7). When attributing heavy rainfall events to El Niño, we should consider the signal-to-noise ratio rather than relying on schematic diagrams such as Figure 4. Attributing droughts is even tricker, as numerous other factors could also play a role.[60]

Could a strong El Niño in 2023-24 propel us into “uncharted territory”? In the simple temperature charts common in global-average land (e.g., Figure 1), it certainly seems plausible. But you can draw your own conclusions after considering the other local charts presented in this article (Figures 5 and 6).

Figure 7 *Seasonal rainfall from December to February, regressed against the El Niño index. White circles show time series locations for Figure 6. (The June-August regressions, which are not shown, are weaker. Data sourced from Global Precipitation Climatology Project).* [***NOTE: This figure is interactive.*** *See Figure 3 caption for details on interactivity.*]

4.3 Counterintuitivity of El Niño

Focusing solely on global averages can be misleading—it is akin to mistaking the symptom for the disease. Narratives set in global-average land are often compelling because

[60] Why El Niño doesn’t mean certain drought (TheConversation.com)

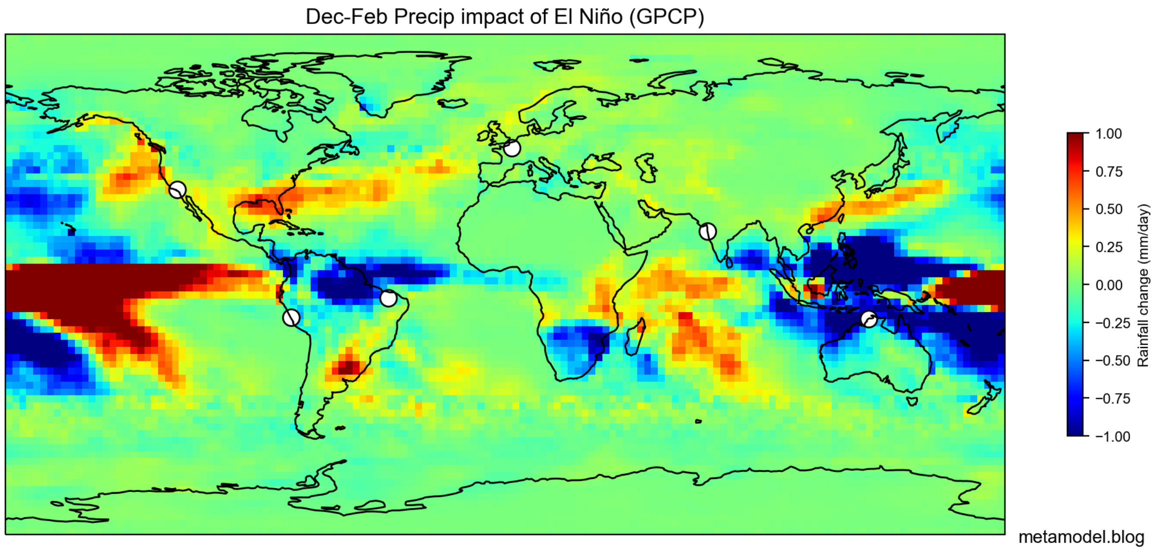

Figure 3: GPCP_DJF_regr

they appear simple. But El Niño is a product of complex interactions between the atmosphere and the ocean that often exhibit counterintuitive behavior.

Will El Niño amplify the impacts of global warming, as one would intuitively expect because it elevates the global-average temperature? That could happen in a few regions, located mostly in the tropics and the subtropics (Figure 3). Elsewhere, El Niño is associated more with cooling than warming, which effectively opposes the effects of enhanced global warming in these regions.

Could El Niño prompt an earlier breach of the 1.5°C threshold? Technically, yes, but practically no! Recall that the original aim of this threshold was to slow the increase in ocean heat content and subsequent sea level rise. Since El Niño is associated with warmer temperatures, one might expect that it will increase the heat stored in the ocean. Indeed, the ocean surface warms during El Niño because cold water stops upwelling to the surface in the eastern tropical Pacific (as the Peruvian fishermen noticed). But the overall heat stored in the whole ocean actually decreases during a typical El Niño event because warmer water loses more heat through evaporation,[61] which means that *El Niño delays the harm that originally motivated the 1.5°C threshold!* It is during La Niña, the opposite phase of El Niña, that the total heat stored in the ocean increases (as it also does in the long-term due to global warming).

Given that the effects of El Niño and La Niña cancel each other in the long-term, it makes little sense to talk about El Niño accelerating or decelerating global warming. However, it is meaningful to wonder whether global warming could amplify El Niño. A simple narrative in global-average land would be that global warming will lead to stronger El Niño episodes, because the ocean is getting warmer. Yet, El Niño is primarily driven by east-west temperature gradients, not absolute temperatures.

The trade winds blow from the cool east to the warm west, pushing the tropical Pacific

[61] "While there are distinct regional … changes, many compensate each other, resulting in a weak but robust net global ocean cooling during and after El Niño." Evolution of Ocean Heat Content Related to ENSO (L. Cheng et al., 2019; Journal of Climate)

waters westward and creating the cool upwelling region off Peru's coast. El Niño temporarily disrupts this process and warms the eastern Pacific. Forecasting the specifics of how these east-west temperature gradients will change in the coming decades turns out to be more challenging than predicting changes in global-average temperature. In fact, climate models have yet to reproduce the cooling trend observed in the eastern tropical Pacific over the last 40 years (Figure 2).[62] (Focusing on model simulations of global-average temperature overlooks important details like this.)

Climate models also disagree on how long-term global warming will affect future El Niño events. Some models predict an increase in the amplitude of El Niño over the next few decades, followed by a decrease by the century's end. Others predict a consistent increase or even decrease in amplitude.[63] This uncertainty means that attributing a stronger than usual El Niño to global warming will be much harder than attributing a heatwave to global warming.

El Niño isn't global warming. We should worry about global warming (in most places), and prepare for El Niño (in fewer places), but we shouldn't conflate the two. We can't prevent or mitigate El Niño. Like the warming associated with sunrise or summer, the warming associated with El Niño is completely natural—albeit more unpredictable. What is not natural is the global warming driven by increasing carbon emissions. We can and should take stronger action to mitigate it.

4.4 Comments

Note: For updated comments, see the original blog post and the anouncement tweet.

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5 Texas Heatwave and Occam's Razor

Did the flapping of a butterfly's wings in Brazil (or elsewhere) cause a heatwave in Texas? Yes, and climate change made it worse. That's the simple explanation.

Metamodel.blog 2023-07-06

[62] Systematic Climate Model Biases in the Large-Scale Patterns of Recent Sea-Surface Temperature and Sea-Level Pressure Change (R.C.J. Wills et al., 2022; Geophysical Research Letters); How the pattern of trends across the tropical Pacific Ocean is critical for understanding the future climate (Climate.gov)

[63] The future of the El Niño–Southern Oscillation: using large ensembles to illuminate time-varying responses and inter-model differences (N. Maher et al., 2023; Earth System Dynamics)

There's a strong heatwave in Texas. Who's to blame? Whodunit, or more precisely, whatdunit? Like the police captain in the movie *Casablanca*, the media reacted to the heatwave by rounding up a gallery of usual suspects:[64] climate change, El Niño, wobbly jetstream, wavy polar vortex, and more. But what do the facts tell us? Is it a complex web of causes or just a couple of key factors?

Unlike murder mysteries and media musings, science focuses on simple explanations. The principle of Occam's Razor says that we should look for the simplest explanation that fits all the facts,[65] and ignore everything else as fluff. In the case of the Texas heatwave, the simple answer to the Whodunit question is[66]:

The Butterfly (Effect) did it, aided and abetted by climate change.

What about other "suspects" that may affect Texas heatwaves: warming because of El Niño, increased waviness of the polar vortex, or just increased thermal energy in the system due to climate change. Oftentimes, the additional explanations just add unnecessary complexity. Sometimes, they actually contradict the historical data!

I live in College Station, Texas, where the heatwave is hitting hard. I also lived through the extreme cold of Winter Storm Uri in 2021. This post is about Texas' extreme weather, which I've personally experienced, and its ties to climate change.

The Texas heatwave can be best explained by two concepts:

[64] Warning of unprecedented heatwaves as El Niño set to return in 2023 (The Guardian), Global heat waves show climate change and El Niño are a bad combo (NPR), The unusual factors behind the extraordinary heat across the southern US (Vox.com)

[65] Occam's (or Ockham's) razor is a principle attributed to the 14th century logician and Franciscan friar William of Ockham: *Pluralitas non est ponenda sine neccesitate*, or Entities should not be multiplied unnecessarily (UCR.edu)

[66] Ch.7, The Climate Demon: Past, Present, and Future of Climate Prediction (ClimateDemon.com)

1. The Butterfly Effect (or chaos theory)[67]
2. Climate change (or global warming)

Chaos theorist Ed Lorenz famously asked the metaphorical question: *Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?*[68] The question highlights how weather prediction is sensitive to small disturbances in initial conditions. The atmosphere is unstable, so little disturbances grow exponentially into large-scale weather phenomena. A heatwave is one such phenomenon, usually linked to long-lasting high pressure systems.[69] One can explain a heatwave by blaming an wobbly jetstream or a wavy polar vortex. But, in essence, these are just elaborate ways of saying that a large-scale weather pattern causes local weather. It's the small disturbances (like the metaphorical butterfly's wing flap) that lead to these large-scale weather patterns and, hence, the heatwave.

The Butterfly Effect explains the cause of the heatwave. But it doesn't tell us how long or severe it will be. That's where factors like climate change come in. Let's look at this using College Station, Texas, where I live, as an example.

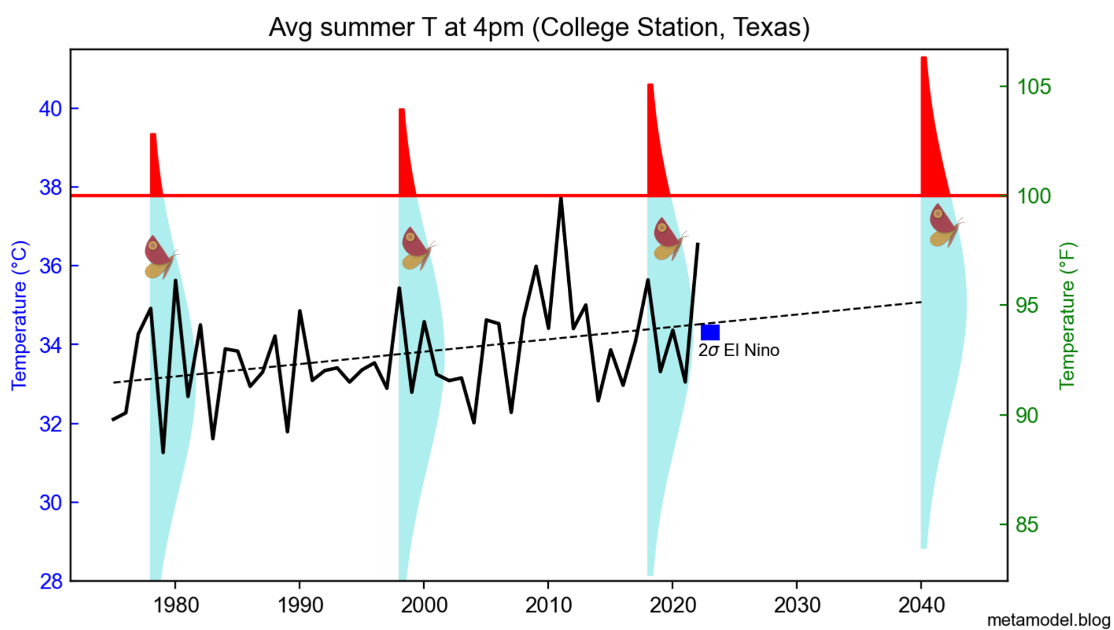

Figure 4: College Station Warming

Figure 1 *Average summer (Jun-Aug) surface (2m) temperature at 4pm for College Station, Texas (solid black line), with linear trend (dashed line). The turquoise area shows a schematic normal distribution for the range of daily weather variability, represented by the butterfly, with the red area showing days with temperature values exceeding 100°F. The small blue bar shows the cooling effect of a strong (2σ) El Niño, as estimated using linear regression.* [From ERA5 reanalysis]

[67] Is the weather actually becoming more extreme? (TED.com), The Butterfly Effect: Everything You Need to Know About This Powerful Mental Model (FS.blog)
[68] When the Butterfly Effect Took Flight (MIT Technology Review)
[69] Anatomy of a heat wave (theclimatebrink.substack.com)

In College Station, the average summer temperature at 4pm, typically the hottest part of the day, has gone up by about 1.5°C (2.7°F) since 1975 (Figure 1). A small change like this can significantly increase heatwave frequency because heatwaves are extreme events in the tail of the temperature probability distribution. Say a butterfly wing flap in 1975 triggered a 99°F heatwave. The same disturbance would trigger a 102°F heatwave in 2023. If we linearly extrapolate the current warming trend, the butterfly will likely trigger a 103°F heatwave by 2040.

The trend in heatwaves over College Station is typical of the general trend for heatwaves over Texas, as shown in Figure 2. This figure, like several others in this post, is taken from a detailed report on climate extremes produced by the Texas State Climatologist.[70] According to the report, the "typical number of triple-digit days by 2036 is projected to be substantially larger, about 40% larger than typical values so far in the 21st century."

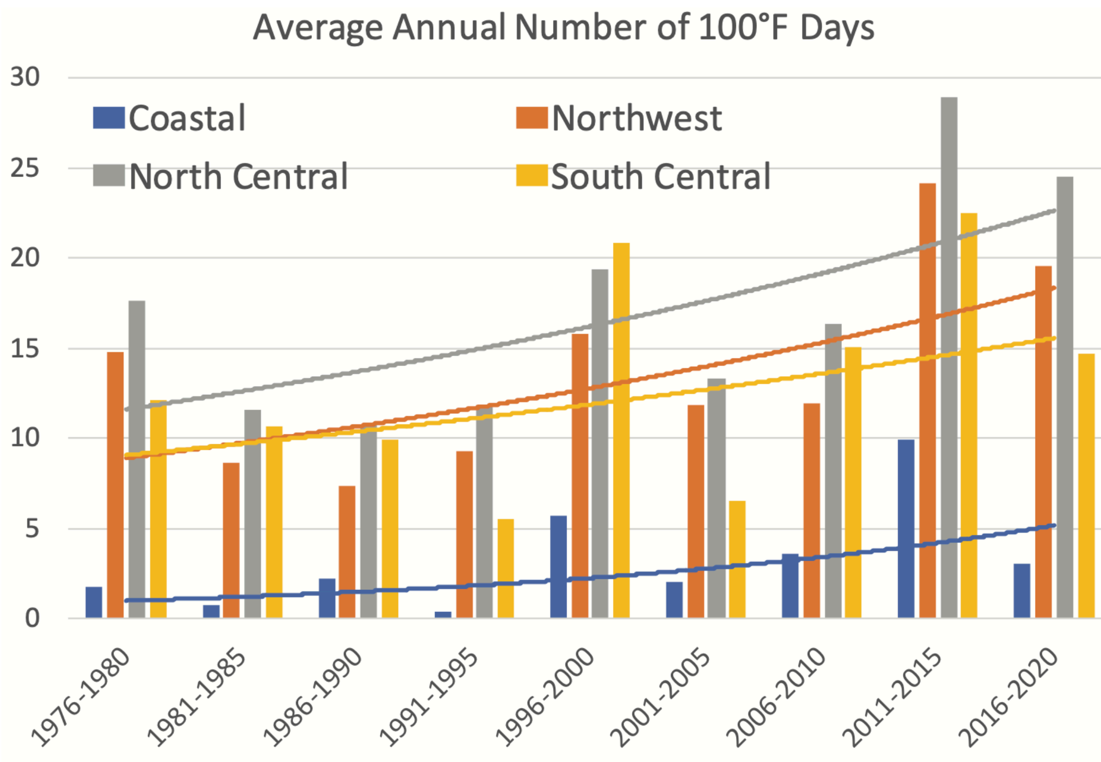

Figure 2 *Trends and historic variability in index temperature stations in Texas. Trend lines are fit to the logarithm of 100 °F day counts to ensure non-negative values.* [From Texas Climatologist Report]

The analysis in this post relies mostly on historical data. As a climate modeler well aware of the limitations of models, I wouldn't recommend using them where one can rely on data instead. Yet, models are essential for linking historical warming to human activity and for predicting future climate change. At the end of this post, I discuss what your options are if—for whatever reason—you do not wish to use climate models even for that purpose.

How does global warming compare to Texas warming

[70] Assessment of Historic and Future Trends of Extreme Weather in Texas, 1900- 2036, 2021 Update. Document OSC-202101 (J Nielsen-Gammon et al., 2021:, Office of the State Climatologist, Texas A&M University)

Does El Niño make Texas heatwaves worse

Will increased thermal energy due to global warming make the weather more extreme

Is climate change making Texas temperature extremes more extreme

What if you are skeptical about climate models

5.1 How does global warming compare to Texas warming?

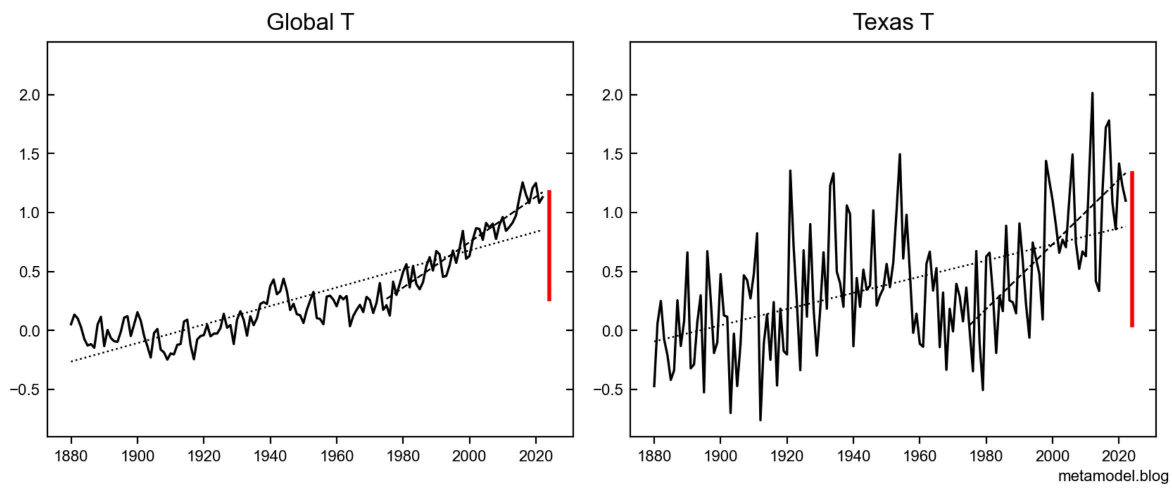

Figure 5: Global and Texas warming

Figure 3 *Global warming vs Texas warming: Annual average surface temperature averaged globally and over the Texas region (26-36N, 94-104W)* [From NASA/GISTEMP]

When we compare global warming to Texas warming, we see some key differences (Figure 3). Globally, the warming trend is clear after 1970. Texas temperatures, on the other hand, vary a lot more from year to year. However, there is a stronger warming trend after 1970. The Butterfly Effect (or internal variability) is largely responsible for these regional variations. [71] When we look at global averages, we filter out a lot of this "noise", as random variations in different regions balance each other out.

How much of the warming since 1970 can we attribute to human activity? We cannot use statistical analysis alone to answer this question, because the monotonic trend in human activities will correlate with just about any other monotonic trend. We need physics-based climate models to make this attribution. These models suggest that human actions caused over 80% of the recent warming (1975-2020) in Texas (Figure 4). They also predict that human-caused warming will continue for the next couple of decades at a rate similar to the recent trend (for a plausible future emission scenario, RCP 4.5). This confirms that the simple linear extrapolation used to predict the future of College Station heatwaves is consistent with climate model projections (Figure 1).

Figure 4 *Simulated and observed surface temperature trends over Texas.* [From Texas Climatologist Report]

[71] Strange weather in the multiverse of climate (Metamodel.blog)

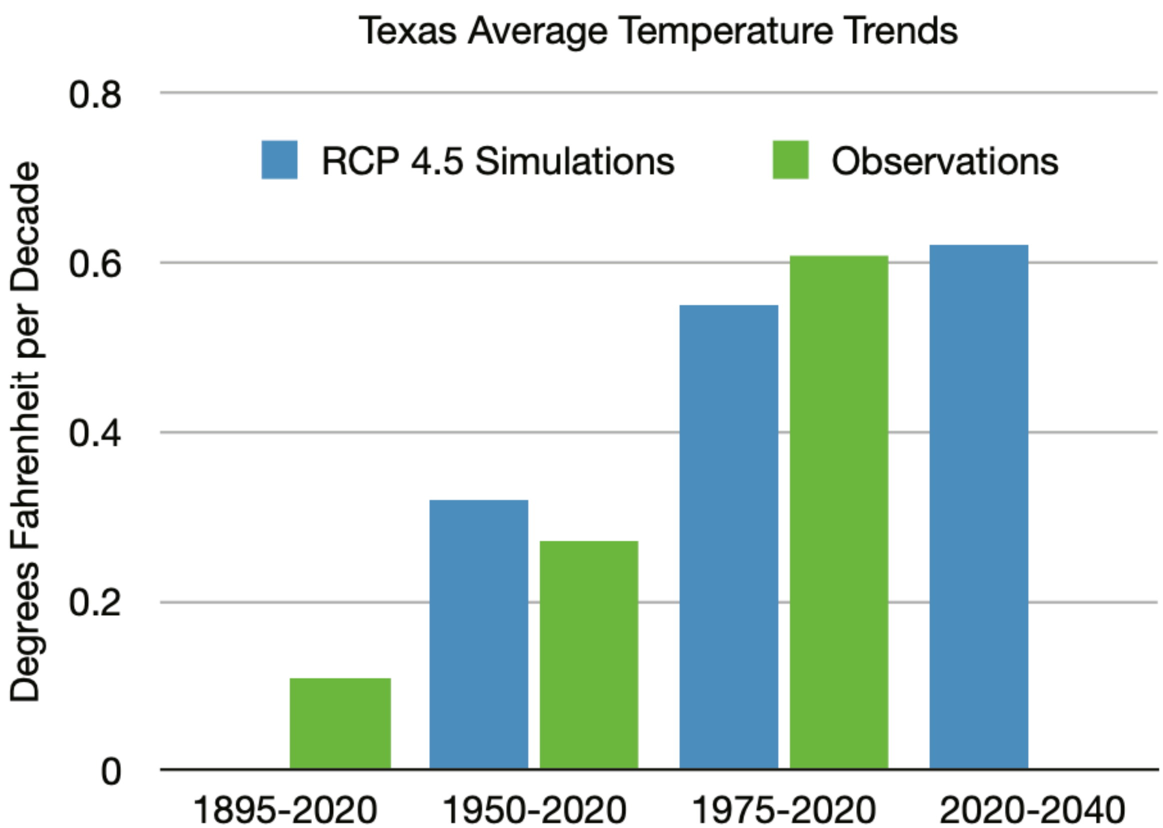

Figure 6: Texas Temperature trends

5.2 Does El Niño make Texas heatwaves worse?

No, the idea that El Niño exacerbates Texas heatwaves is at odds with historical records. Past data indicates that El Niño actually cools Texas during summer, which would make heatwaves milder. A strong El Niño could decrease College Station's temperature by about 0.4°C (0.7°F) (Figure 4). A prior post on this blog discusses why El Niño doesn't always amplify heatwaves, even though it can increase the global average temperature.[72] El Niño spreads out from the tropical Pacific as a dynamic wave effect, with alternating positive and negative signs of remote regional impacts. In contrast, global warming is a localized thermodynamic effect that tends to warm all regions.

5.3 Will increased thermal energy due to global warming make the weather more extreme?

As the earth heats up, the amount of thermal energy increases. Some argue that this makes all weather events more extreme, resulting in more severe heatwaves and cold spells. While this is a plausible argument motivated by physics, it only applies to homogeneous systems in statistical-mechanical equilibrium, where a single variable, temperature, characterizes the entire system. However, climate is an inhomogeneous system that is far from statistical-mechanical equilibrium. So there is no simple physical relationship between absolute temperature and its variability.

The instability in the atmosphere and resulting weather is mainly controlled by temperature gradients, not absolute temperature. Global warming is causing the poles to heat up faster than the equator, which reduces this gradient and could weaken weather systems. (However, factors like increased humidity and spatial inhomogeneity could counteract this to some extent.) The latest IPCC report[73] shows that the coldest temperatures are not becoming more severe but are warming (Figure 5), as we might expect when surface temperature increases everywhere.

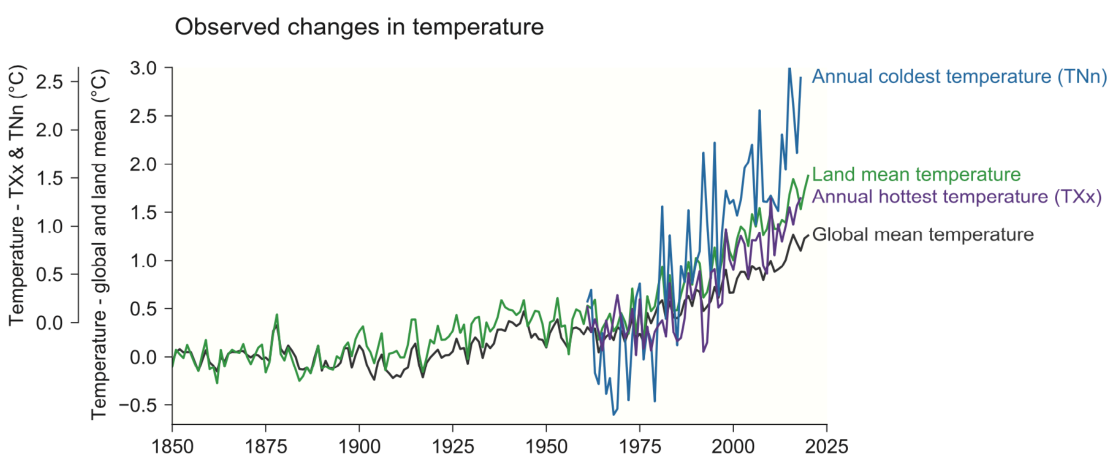

Figure 5 *Time series of observed temperature anomalies for global average annual mean temperature (black), land average annual mean temperature (green), land average annual hottest daily maximum temperature (TXx, purple), and land average*

[72] Who's afraid of the Big Bad El Niño? (Metamodel.blog)

[73] "Widespread observed and projected increases in the intensity and frequency of hot extremes, together with decreases in the intensity and frequency of cold extremes, are consistent with global and regional warming." p.1523, IPCC AR6 WG1 Report

annual coldest daily minimum temperature (TNn, blue). [Figure 11.2 from IPCC AR6 WG1 Report]

5.4 Is climate change making Texas temperature extremes more extreme?

A prevalent theory suggests that global warming makes the polar vortex more wavy, resulting in extreme weather, both heatwaves and cold spells. That would mean that both the hottest temperatures and the coldest temperatures should set new records. But has this been happening in Texas?

According to the climatologist report, extreme hot summer temperatures in Texas have been increasing since 1975, but not as fast the average summer temperature (Figure 6). This means that the summer temperature probability distribution for College Station shown in Figure 1 may narrow slightly as Texas warms.

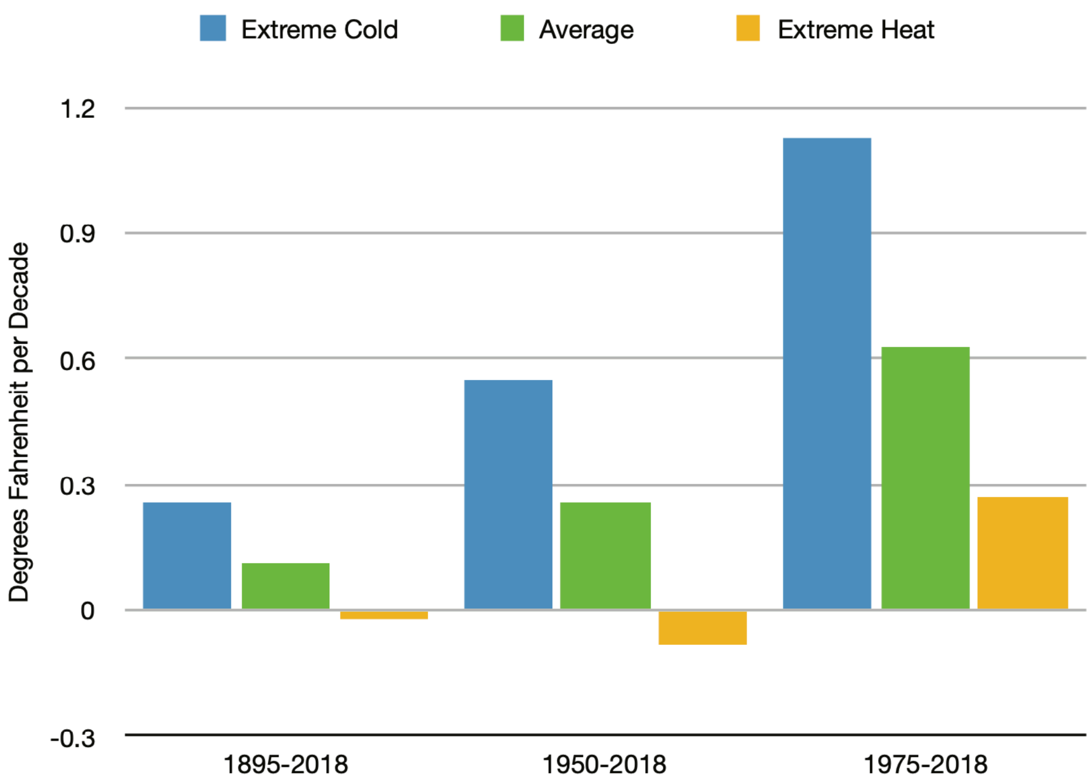

Figure 6 *Comparison of the sizes of the trends in average temperatures and extreme heat and cold in the county data* [From Texas Climatologist Report]

Meanwhile, the coldest winter temperatures in Texas are warming (Figure 6), similar to global trends (Figure 5). How then do we explain the occurrence of extreme Winter Storm Uri in 2021? Simple, the Butterfly Effect! Global warming didn't cause Winter Storm Uri. On the contrary, the warming likely made the storm milder. Media continue to link such severe winter storms to climate change,[74] but historical data from Texas

[74] The Texas Power Grid Failure Is a Climate Change Cautionary Tale (TIME.com)

refutes the idea that a wavier polar vortex is making winter temperature extremes more severe due to climate change.

5.5 What if you are skeptical about climate models?

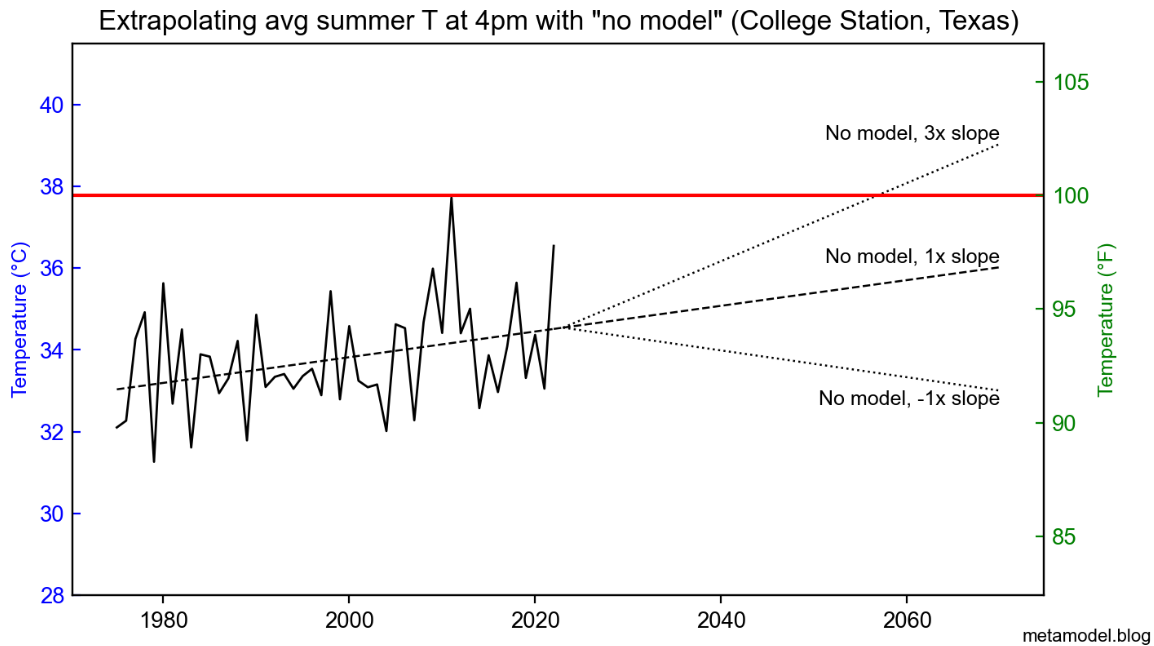

Figure 7: Temperature extrapolation

Figure 7 *Variation of Figure 1 showing three hypothetical "no model" projections of the future: reversing the recent warming trend, sustaining it, or accelerating the trend.*

If you're skeptical about climate models, consider that Texas's climate is changing, with a clear warming trend and an increase in 100-degree days over the past 50 years (Figure 2). How do you plan for the future without relying on climate models? You need to consider the possibility that the warming trend could reverse, continue, or even accelerate, as shown in Figure 7.

You may think Figure 7 doesn't use a model, but it is actually using a simple statistical model. The point is that any planning requires a prediction model. The only way to avoid models altogether is not to think about the future at all!

If you want to plan for the future, there are basically two options:

1. Reductionist physics-based models: Reductionist models, like the ones used by IPCC, break the complex climate system into components, and handle each component separately. These models aren't perfect; they have uncertainties and biases. However, their components and their combined predictions are validated against data. We can test the components using short-term measurements, without the need for centuries of validation data.
2. Emergent statistical models: Emergent models try to predict climate properties like temperature statistically, without breaking the climate system down into pieces. These models will necessarily be crude, like the one shown in Figure 7,

> because we have limited historical data to validate them. Climate varies across many timescales, from decades to millennia, and we have reliable data only for about a century or so.

Simple statistical models may be adequate for short-term climate predictions of up to a decade or so. (They may even be preferable to the physics-based models in some cases because they avoid simulation biases.) In the longer term, though, statistical models will not capture the nonlocal and nonlinear interactions that affect climate, including the projected impact of changing human activities.

Finding flaws in physics-based climate models isn't hard, but there is no better alternative for long-term prediction. How much should we trust the predictions from physics-based models? As Figure 7 shows, the worst-case scenario using a crude statistical model could be more severe than those predicted by the IPCC climate models. Physics-based models, for all their imperfections, are subject to strict energy and mass constraints that limit the range of future climate changes. Poorly validated extrapolative statistical models are not so constrained.

5.6 Comments

Note: For updated comments, see the original blog post.
