One Earth

Gold Standard for the Global Goals
1 ton of CO_2 offset

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Commentary

Uncertainties in Climate and Weather Extremes Increase the Cost of Carbon

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Climate change has myriad physical and economic impacts. Even those that can be easily quantified indicate the need for ambitious climate action. Other climate impacts have yet to be quantified. We argue here that uncertainties in climate and weather extremes only further increase the social cost of carbon emissions.

Climate change is among the most long-term, global, uncertain, and, in human timescales, irreversible public-policy problems. It is unique in the combination of all four.[1] Climate change is also beset with important tradeoffs between short-term economic pain and long-term gain. It is crucial then to have an objective measure of how damaging unmitigated climate change is and how ambitious policy ought to be if we are to avoid climate-related damages. Capturing these tradeoffs is the purvey of what might be the world's most ambitious benefit-cost analysis. That analysis is often summarized in a single metric: the social cost of carbon (SCC).

Although precise definitions vary, the goal of the SCC is to quantify the tradeoffs between the benefits and costs of cutting CO_2 emissions and to capture them in a single number: the price that society pays for emitting a marginal ton of CO_2.[2] The SCC is also the price that each of us *should* pay for emitting an additional ton. The SCC is important for designing policies such as carbon prices. More broadly, the SCC summarizes the urgency of dealing with climate change. A low SCC would be grounds for delaying transformative changes to our energy infrastructure. A high SCC, meanwhile, indicates that we will pay dearly for not acting decisively now.

The SCC, as a measure of the cost of emitting another ton of CO_2, also has some very real limitations, not least how it deals with uncertainty. In particular, the SCC is highly sensitive to uncertainty in both climate and weather extremes. The first captures the probability of extreme overall climate change, typically represented by extreme values of equilibrium climate sensitivity (ECS), the metric that scientists use to summarize the link between CO_2 and global warming. Specifically, ECS translates a doubling of atmospheric CO_2 concentrations into eventual global average temperature rise. It has been persistently difficult to pin ECS down in that "likely" estimates for decades have ranged from 1.5°C to 4.5°C per doubling of CO_2. Global warming of even 1.5°C would have vast impacts on many Earth systems. Warming of 2°C, 3°C, or even 4°C would be exponentially worse. Worse yet, we cannot fully exclude values as high as 6°C or more.[1,3]

The second limitation focuses on how the impacts of climate change are highly sensitive to the frequency and intensity of extreme weather events, such as floods, droughts, or tropical cyclones. Those changes might be significant even for a moderate amount of overall warming.

Here, we argue that both extreme climate change and extreme weather, in turn, lead the most current SCC estimates to be biased toward lower values, often significantly so. By underestimating the SCC, we are underestimating the need for drastic climate action.

Estimates of Social Cost Are Biased Downward

Both the benefits and costs of cutting CO_2 are very likely biased toward lower SCC estimates. On the cost side, most climate-economy models fail to account for how technological progress and the deployment of new low-carbon technologies depend on investment over time.[4] Research, development, and deployment of new technologies do not happen in a vacuum but are rather the result of today's innovators' "standing on the shoulders of giants" and of learning by doing. That implies the need for a higher SCC today so we can more cheaply cut CO_2 emissions in the (near) future.

The primary reason why SCC estimates are biased downward, though, is most likely found on the benefit side of the equation.[2] Calculating the benefits of cutting CO_2 emissions—or, conversely, the costs of unmitigated climate change—involves two main steps: one physical and one economic. The first links the marginal ton of emitted CO_2 to the resulting warming, and the second links it to the resulting economic impacts. Both the magnitude and damages of future climate change are beset with significant and recalcitrant uncertainties,[5] translating into large uncertainties in the SCC. As a result, the SCC is often presented as a draw of outcomes from a simulation exercise that generates a distribution of possible outcomes around a particular median or central estimate.

If the central SCC value presented is indeed a median estimate, there ought to be a 50% chance that its true value is lower and a 50% chance that its true value is higher. The US Government Interagency Working Group on Social Cost of Carbon in President Barrack Obama's administration, for example, presented a central value of around $40 for each ton of CO_2 emitted now.[2] That number is the average across the three most prominent climate-economy models that calculate the SCC: DICE, developed by Bill Nordhaus; FUND, originally developed by

Richard Tol; and PAGE, developed by Chris Hope. The government working group made some adjustments to unify assumptions across models but otherwise stuck to the model structures. The $40, meanwhile, is far from an unbiased central estimate.

Uncertainties in Extremes Bias the Cost of Carbon

To understand why current SCC estimates are biased, it is instructive to use the classification made famous by former US Secretary of Defense Donald Rumsfeld: there are "known knowns," "known unknowns," and "unknown unknowns."

Known knowns are the main ingredients that go into present SCC calculations: the climate damages that are already *quantitatively* accounted for. On the physical climate side, they include current estimates of the magnitude of future climate change, quantified through metrics such as the ECS. These physical estimates are then translated into economic estimates of climate damages, quantified through econometric techniques, often based on extrapolating historical estimates.[2,6]

These known knowns already take into account uncertainties in both climate change and its damages but only to the degree that they are *quantitatively* and accurately represented. However, it is clear that our accounting of uncertainty in the magnitude and consequences of climate change is far from complete. Crucially, because damages are generally represented as a function of overall warming and often rely on global approximations for damages, there is no direct accounting for changes in extreme events. Accounting for these unknowns only increases damages further. These unknowns, in turn, can be split into two distinct categories.

Known unknowns can be broadly separated as either economic or physical. From a climate-economic perspective, they are climate damages that are known to science but have not yet been assigned a dollar value by climate economists. Call them "unquantified quantifiables." Efforts such as the Climate Impact Lab (http://www.impactlab.org/) have made significant progress in estimating the costs of climate damages across a number of domains.[6] The more such damages can be quantified and move from the quantifiable into the quantified column, the greater the benefits of cutting CO_2 emission, as well as the resulting SCC, will be.

From the physical-climate perspective, known unknowns present climate uncertainty in the true Knightian[7] sense of the term. This uncertainty manifests itself in two ways: epistemic and aleatory. Epistemic uncertainty, or uncertainty in our knowledge of how Earth's climate responds to CO_2 emissions, includes factors such as how changes in cloud cover will feed back into surface warming. Aleatory uncertainty, or natural variability, includes the fact that even if we can predict the overall climate a hundred years from now, we still won't be able to predict the weather more than a few weeks out.

The interaction between epistemic and aleatory uncertainties is particularly critical because uncertainty in how much global warming we will experience compounds the uncertainty in how (extreme) weather events will change for a given amount of global warming. This uncertainty is, in principle, quantifiable. We mostly understand how weather and climate processes work in isolation—scientists can model both individual clouds and can predict individual hurricanes. The limit is mostly computational. Limits in computing power prevent us from putting everything together into an accurate forecast of long-term climate change. Thus, models are incomplete in mostly *known* ways.

Quantifying these qualitatively understood sources of uncertainty will tend to skew SCC estimates toward larger values. Even small changes in mean warming can lead to large changes in the probability of extreme temperatures, which in turn can have devastating consequences on everything from agricultural yields[8] to human health.[9] Although the precise nature of changes in other types of extreme weather events is still hard to quantify, it is generally accepted that events such as hurricanes and floods intensify with global warming. Because economic damages are particularly large for extreme events, any such increase in their intensity will have an outsized impact on the SCC.[2,9] For example, Hurricane Harvey, which hit Texas in August 2017 and was very likely intensified by global warming, accounted for larger economic costs from climate change than climate-economy models assumed for the entire year.[10] Additionally, many of the *known* processes that are poorly quantified, such as effects from clouds, have significantly more potential to amplify rather than dampen warming.[11] All of this means that we are probably underaccounting for the probability of extreme warming and of more intense weather extremes.

This also puts the third Rumsfeldian category—unknown unknowns—into perspective. It is nearly impossible to completely account for the myriad possible interactions between the various components of the climate system. And the world is riding this complex system into a state for which there is no good analog in over a million years. This makes forecasting climate change a fundamentally tricky out-of-sample prediction problem. Surprises are sure to exist, and if they could be quantified, they would also primarily push the SCC toward higher values.

For one, there is a lot of room on the extreme warming tail of ECS, whereas values of ECS lower than about 1°C can be ruled out given that global average temperatures have already risen by as much, even though CO_2 has yet to double from pre-industrial levels. This skews uncertainties in long-term physical climate impacts toward higher rather than lower temperatures.

The more fundamental reason for why unknown unknowns should increase the SCC are ever-present threshold effects.[3] Let's assume, for example, that we do not even know whether the intensity of extreme hurricane storm surges will increase or decrease, and let's even allow for symmetric uncertainty: it's just as likely that storms will intensify as it is that they will weaken. Because flood barriers such as dams and sea walls are designed around thresholds, the damage is essentially zero as long as the threshold is not exceeded. Allowing for the probability that floods and storm surges become less intense thus does not decrease the risk profile. Allowing for the probability that floods and storm surges might overwhelm the barriers, meanwhile, leads to potentially large additional risks. Thus, even symmetric uncertainty in how extreme events will change nonetheless leads to potentially large increases in climate damages and thus the SCC.

The tendency to underestimate the SCC comes from a set of compounding factors: unquantified physical uncertainty tends to both drive up the probability of extreme climate change and make extreme weather events more so. Moreover, damages increase rapidly with both overall warming and changes in extremes. The net effect on the SCC is clear: the larger the uncertainties, the larger the SCC.[12] In fact, the SCC can be broken down into two components: expected damages (those that can be measured and quantified) and risk aversion (the part of the SCC that puts a price on risks and inherent uncertainties). Some go a step further and add uncertainty or "ambiguity" aversion to the equation.[13] Both increase the SCC further still, sometimes decisively so.

Social, economic, and geo-political interactions are even more complex and more prone to unpleasant surprises than the physical climate. Extreme socio-economic events might thus be more important than climatic ones.[14] Some civil conflicts are already attributable to climate changes.[15] The potential of retreating Himalayan glaciers to alter patterns of runoff, irrigation, and floods and thus increase tensions over water at the India-Pakistan border is another example.

Uncertainty Is Not Our Friend

The uncertainty in the consequences of climate change has often been advocated as a reason to delay action. An oft-used technique by vested interests intent on delaying effective climate policy is to point to inherent climate uncertainties and thus attempt to sow doubt among policymakers and the wider public.[16] "We don't yet know for sure," the argument goes, "so we better wait and see and do more research." Quite the contrary. As our knowledge advances, it is much more likely that the true SCC will reveal itself to be larger than current estimates. It is precisely the uncertainties that make climate change so costly. The true SCC is surely significantly higher than the $40 largely based on highly conservative assumptions. Well-founded estimates by now go as high as $200,[17] $400,[18] and more.

There are many important extensions of this work: some conceptual and many empirical. Some could well lead to reasons to believe that the SCC should be lower than previously assumed, indicating that it is possible to ease off the need to cut CO_2 emissions. Significant technological advances in carbon-removal technologies come to mind. Most, sadly, won't. Uncertainties and climatic extremes add even more need for more stringent climate policy. That stringency should be reflected in a higher true SCC.

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