Uncertainty: Concepts and Philosophy

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OVERVIEW

1. What is uncertainty?
2. The importance of uncertainty assessment
3. Uncertainty models and budgets
4. The quality of uncertainty estimates
5. The ethics of uncertainty assessment

1. What is uncertainty?

LEARNING ABOUT QUANTITIES

- In both measurement and modeling, we are often interested in learning about *quantities*.
  - **Quantity** – a property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a unit [adapted from JCGM VIM 2012].
- (In modeling, the quantity of interest is sometimes only hypothetical, e.g., the temperature that the ocean surface in a location would have at a future time under a particular ghg scenario.)
- Our efforts culminate in a result that assigns a value to the quantity, e.g., T = 19.7 Celsius, which has some associated uncertainty.

Is the uncertainty a property of the result…

…or is it a property of <u>us</u>?

THE ERROR VIEW OF UNCERTAINTY

- Uncertainty is a property of a result. It is the magnitude of total possible error in the result – its possible deviation from the true value – which depends on the process by which it was produced.
  - *Random error:* "component of measurement error that in replicate measurements varies in an unpredictable manner" (VIM3, p. 23).
  - *Systematic error*: component of measurement error that "in replicate measurements remains constant or varies in a predictable manner" (VIM3, p. 22).
- A criticism: This view "focus[es] on *unknowable* quantities: the 'error' of the result of a measurement and the 'true value' of the measurand" (JCGM 2008, p. 3).

THE EPISTEMIC VIEW OF UNCERTAINTY

- Uncertainty is a property of us. An uncertainty estimate characterizes the extent to which we are currently unable to exactly determine the best value to assign to the quantity.
  - "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand" (JCGM 2008, p. 2).
- Our inability to exactly determine the value can stem from our awareness of *random effects* in the measurement process, uncertainty about how to correct for recognized *systematic effects*, and even ambiguity in the way the quantity is *defined*.
- Note that small uncertainty on this view does not necessarily imply small error!
  - "…even if the evaluated uncertainties are small, there is still no guarantee that the error in the measurement result is small; for . . . a systematic effect may have been overlooked because it was unrecognized. (JCGM 2008, p. 51)

AN EXAMPLE…

$$T = 19.7 \pm 0.3 \text{ Celsius}$$

- *Error view*: The estimate of T is (very probably) not more than 0.3 C from the true value.
- *Epistemic view*: We can reasonably assign T values between 19.4 and 20.0 C.

AND HYBRID VIEWS ARE POSSIBLE TOO…

- Uncertainty is a property of us. An uncertainty estimate characterizes the extent to which we are currently unable to exactly determine the true value of the quantity.

- Do we have to choose a single view?
- I don’t think so. Different views may be more appropriate in different circumstances.

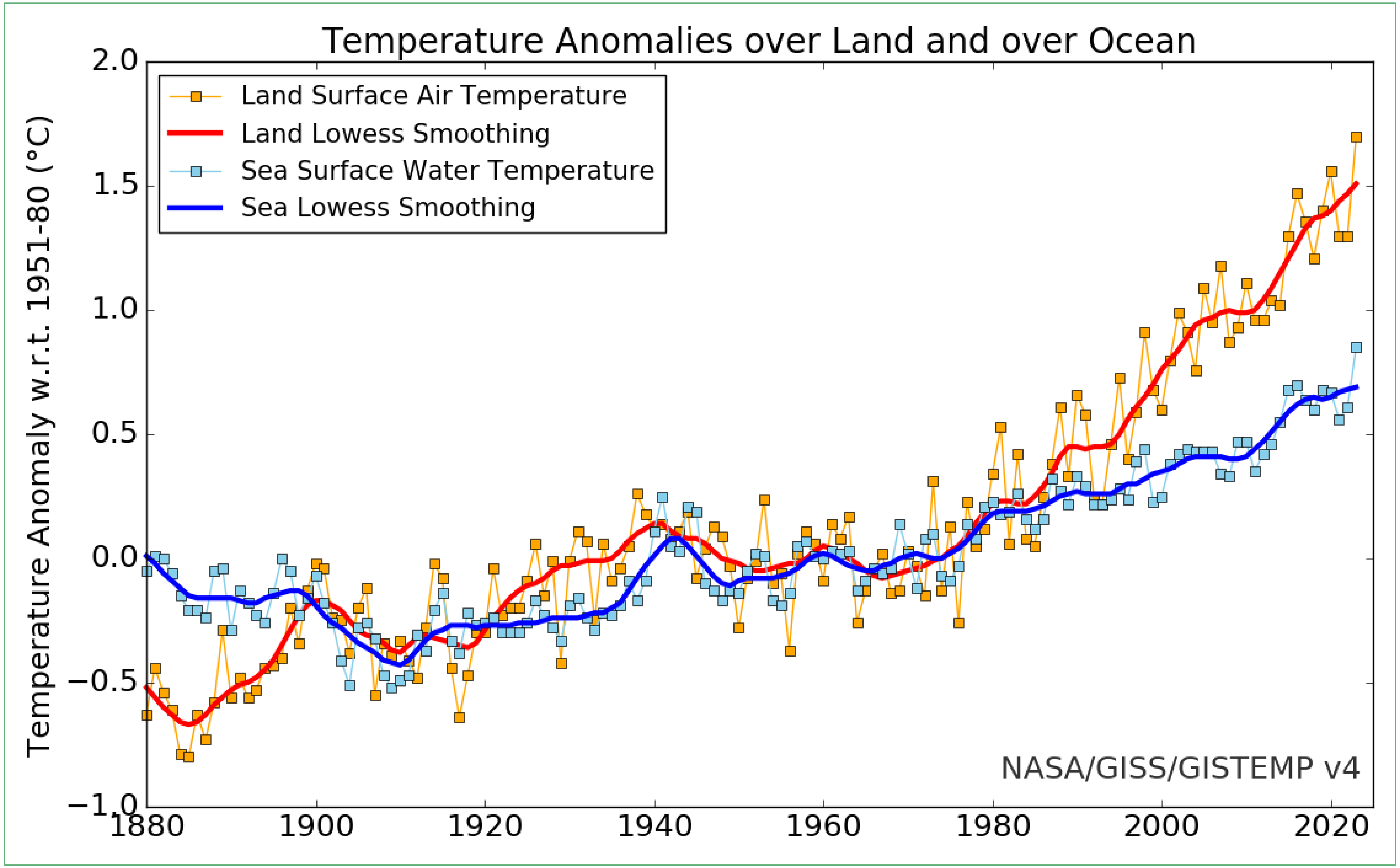
2. The importance of uncertainty assessment

WHY BOTHER TO ASSESS UNCERTAINTY?

- It's just good practice.
- Your paper might not get published unless you discuss the uncertainty associated with your results.
- It's unclear what we can infer from a result without information about its associated uncertainty!!

Was SST in 2020 more than 0.5C warmer than in 1950?

We can't answer confidently without uncertainty info!



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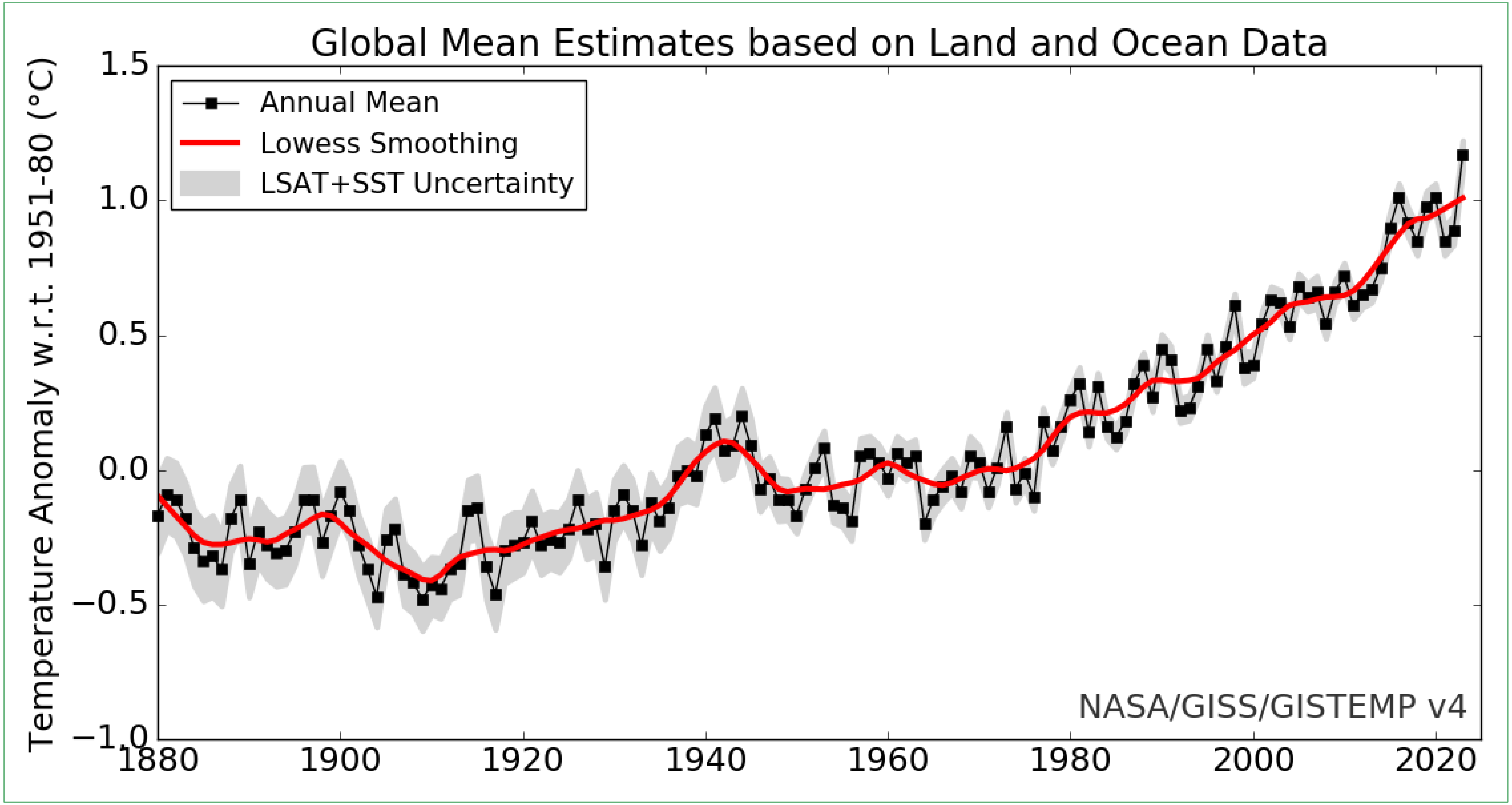
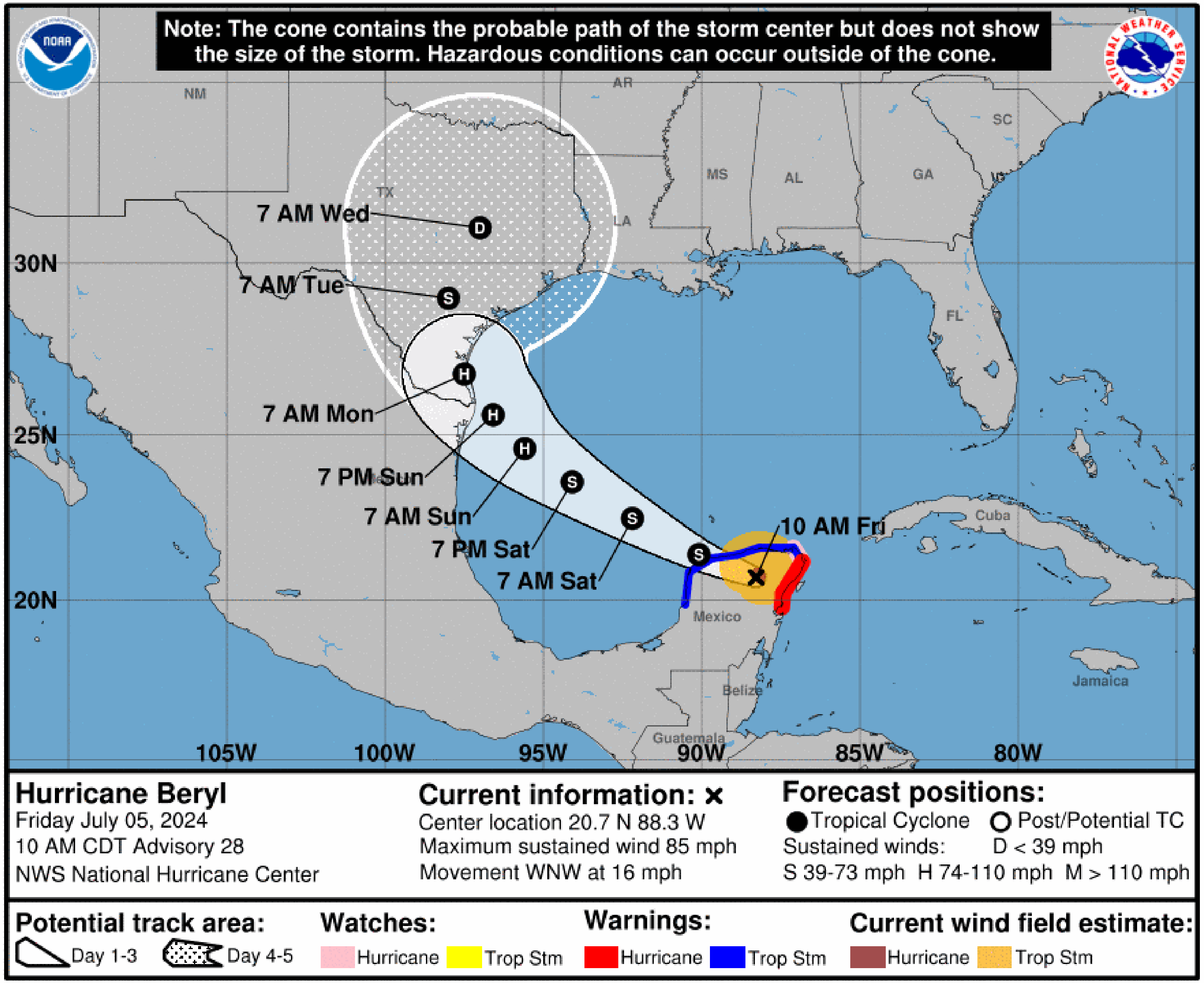


https://data.giss.nasa.gov/gistemp/graphs_v4/

UNCERTAINTY INFORMATION IS NOT AN OPTIONAL ADD-ON…

- A complete measurement result includes an estimate of the value of the quantity, plus uncertainty information.
  - “In general, the result of a measurement is only an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty of that estimate.” (JCGM 2008, p. 4)
- Likewise, in meteorology there is the adage that a forecast is incomplete without information about of its associated uncertainty.



https://www.nola.com/news/hurricane/hurricane-beryl-louisiana-cone-of-uncertainty/article_30fc0886-3adc-11ef-a57b-d38b2639c12f.html

3. Uncertainty models and budgets

VARIETIES OF UNCERTAINTY ASSESSMENT

- Uncertainty assessment can be qualitative or quantitative, and more or less rigorous.
- Qualitative uncertainty assessment might involve, for instance:
  - listing the main sources of uncertainty affecting the measurement process
  - flagging data points in which there is relatively low confidence (because of how they were produced)
- Qualitative information is better than providing no uncertainty information at all!
- But community standards in many domains have been evolving to expect (or at least to value) quantitative uncertainty estimates produced via a formal uncertainty analysis.

UNCERTAINTY BUDGET

A quantitative accounting of component sources of uncertainty in a measurement or modeling procedure, which includes estimates of the contributions from the component sources and combines those contributions in order to arrive at an estimate of the total uncertainty associated with a result.

Sources of Uncertainty in Length Measurement	Value of Uncertainty
Uncertainty due to imperfect manufacture/calibration of metal tape measure.	0.2 mm
Bending of measuring tape during measurement	0.3 mm
Thermal expansion of measuring tape	0.1 mm
Reduction in string length due to string not lying straight	3.0 mm
Variation due to stretching or shrinking of string	2.0 mm
Uncertainty due to aligning tape with frayed ends of string	2.0 mm
Length deviation due to tape & string not being parallel	0.5 mm
Resolution limits reading numerical value from tape	0.5 mm
Combined uncertainty:	**4.2 mm**

Table 1: Example of an uncertainty budget for measuring the length of a string (inspired by Bell 1999, p. 21 & JCGM 2020, p. 23). Taking the square root of the sum of the squares yields the combined uncertainty. The measured value plus/minus the combined uncertainty yields a 1σ confidence interval.

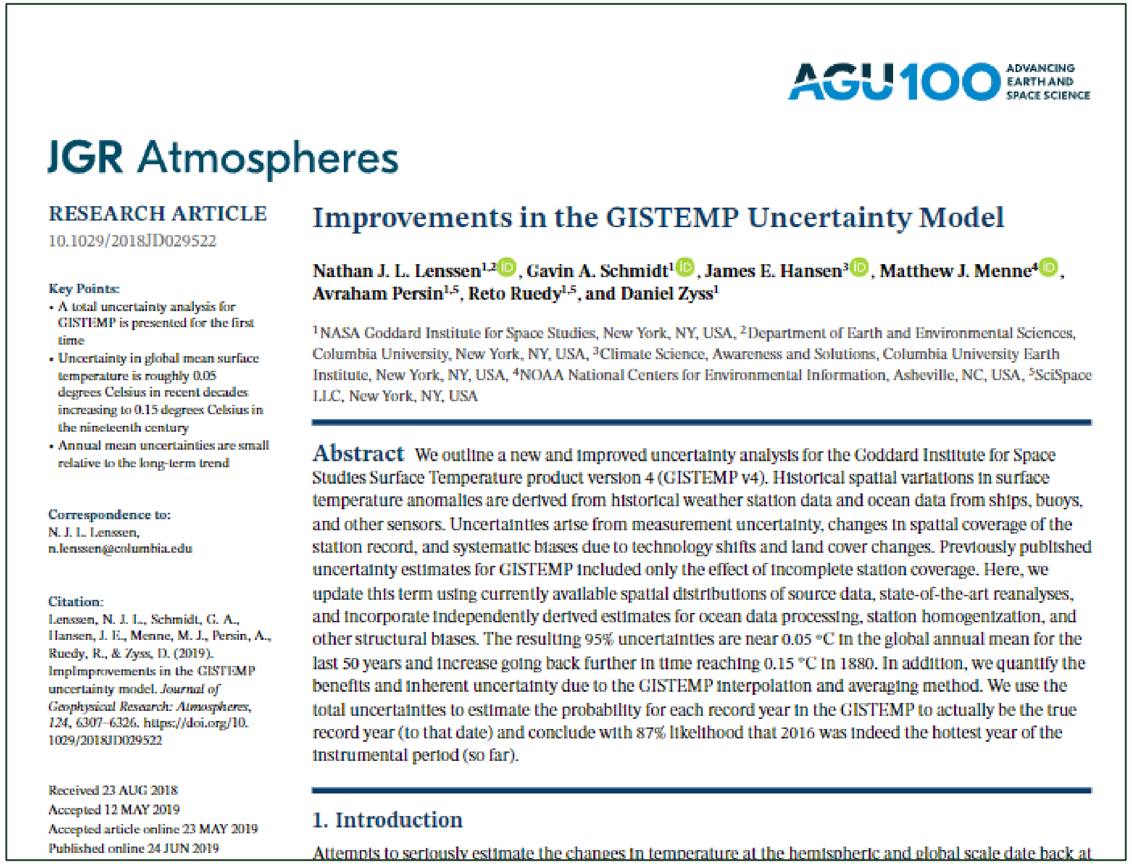
UNCERTAINTY MODEL

- A similar approach involves an *uncertainty model*, in the form of an equation:

$$U = f(u_1, u_2, u_3, \ldots),$$

where U is the total uncertainty and $u_1 \ldots u_n$ are component contributions from different sources, which need to be estimated.

- (Calculating the combined/total uncertainty using an uncertainty budget requires such a model too.)



AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR Atmospheres

RESEARCH ARTICLE

10.1029/2018JD029522

Key Points:

- A total uncertainty analysis for GISTEMP is presented for the first time
- Uncertainty in global mean surface temperature is roughly 0.05 degrees Celsius in recent decades increasing to 0.15 degrees Celsius in the nineteenth century
- Annual mean uncertainties are small relative to the long-term trend

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Improvements in the GISTEMP Uncertainty Model

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Abstract We outline a new and improved uncertainty analysis for the Goddard Institute for Space Studies Surface Temperature product version 4 (GISTEMP v4). Historical spatial variations in surface temperature anomalies are derived from historical weather station data and ocean data from ships, buoys, and other sensors. Uncertainties arise from measurement uncertainty, changes in spatial coverage of the station record, and systematic biases due to technology shifts and land cover changes. Previously published uncertainty estimates for GISTEMP included only the effect of incomplete station coverage. Here, we update this term using currently available spatial distributions of source data, state-of-the-art reanalyses, and incorporate independently derived estimates for ocean data processing, station homogenization, and other structural biases. The resulting 95% uncertainties are near 0.05 °C in the global annual mean for the last 50 years and increase going back further in time reaching 0.15 °C in 1880. In addition, we quantify the benefits and inherent uncertainty due to the GISTEMP interpolation and averaging method. We use the total uncertainties to estimate the probability for each record year in the GISTEMP to actually be the true record year (to that date) and conclude with 87% likelihood that 2016 was indeed the hottest year of the instrumental period (so far).

1. Introduction

Attempts to seriously estimate the changes in temperature at the hemispheric and global scale date back at

TAKING ACCOUNT OF OTHER RESULTS…

- Uncertainty budgets and models often consider only sources of uncertainty internal to the measurement or modeling activity at hand, perhaps in line with the error view.
- But sometimes there are *other* estimates of the same quantity available.
- From an epistemic/hybrid view perspective, we should take this info into account in arriving at a final estimate for the quantity.
- It can be hard to know how best to do so.

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Dataset	Period of Record	Land Component	SST Component	Ensemble Uncertainties?	Meets all Inclusion Criteria?	Principal Reference
HadCRUT5	1850–2020	CRUTEM5	HadSST4	Yes	Yes	Morice et al. (2021)
NOAA GlobalTemp – Interim	1850–2020	GHCNv4	ERSSTv5	Yes, on earlier version	Yes	Vose et al. (2021)
Berkeley Earth	1850–2020	Berkeley	HadSST4	No	Yes	Rohde and Hausfather (2020)
Kadow et al.	1850–2020	CRUTEM5	HadSST4	No	Yes	Kadow et al. (2020)
China – MST	1856–2020	CLSAT	ERSSTv5	No	Land only	Sun et al. (2021)
GISTEMP	1880–2020	GHCNv4	ERSSTv5	Yes	Post-1880 only	Lenssen et al. (2019)
Cowtan and Way	1850–2020	CRUTEM4	HadSST3	Yes	No	Cowtan and Way (2014)
Vaccaro et al.	1850–2020	CRUTEM4	HadSST3	No	No	Vaccaro et al. (2021)

uncertainty model. *Journal of Geophysical Research: Atmospheres*, *124*, 6307–6326. https://doi.org/10.1029/2018JD029522

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4. The quality of uncertainty estimates

HOW CAN WE ASSESS THE QUALITY OF UNCERTAINTY ESTIMATES?

1. Are major sources of uncertainty accounted for?
2. Is the assessment of their contributions done in a careful, well-motivated way?
3. Are the contributions combined in a sensible way to estimate the total uncertainty?

IMPROVING UNCERTAINTY ESTIMATES

- The quality of an uncertainty estimate can be improved by:
  - accounting for more of the sources of uncertainty actually present
  - refining the estimated contributions from individual sources of uncertainty
  - Improving how these contributions are combined
- Uncertainty estimates are sometimes *iteratively* improved over time in these ways, especially when datasets are produced for general usage by a community.
- But improvement needn't mean smaller uncertainty; accounting for a previously unrecognized source of uncertainty could significantly *increase* the total uncertainty.

ADEQUATE UNCERTAINTY ESTIMATES

- In practice, it can make sense to evaluate uncertainty estimates in terms of their adequacy for particular purposes of interest.
- Measurements and modeling results are often used for scientific purposes for which coarser information about the quantity will be sufficient.
  - discriminating among competing hypotheses
  - informing a practical decision
  - identifying a fruitful pathway for further research …
- For many purposes, a complete uncertainty estimate will not be needed; attempting to produce one may even be counterproductive, given limited time/resources.

5. The ethics of uncertainty assessment

MISREPRESENTATION OF UNCERTAINTY CAN HAVE CONSEQUENCES

- When presenting an uncertainty estimate, it's good practice to clearly communicate the extent to which the uncertainty assessment is incomplete or otherwise limited.
  - *Example*: "We have propagated uncertainties associated with model inputs, but we have not taken account of structural model uncertainty, which is likely to be significant."
- This is especially so when results might be used to inform consequential decisions, e.g., for climate change adaptation.
- Misrepresentation of uncertainty in these circumstances can have serious, harmful consequences.

HOW CAN UNCERTAINTY BE MISREPRESENTED?

- We might simply make a mistake in our uncertainty analysis. Mistakes happen. But when the stakes are high, extra effort should be made to avoid mistakes.
- We might present an uncertainty estimate as if it is complete, when we should recognize that significant sources of uncertainty have not been taken into account.
- We might represent uncertainty with false precision, e.g., providing a PDF, implying that we can assign precise probabilities to different values for the quantity, when in fact uncertainty is ‘deeper’ than this.

TWO BASIC CRITERIA FOR CONSEQUENTIAL UQ

- Completeness: we should strive to take account of all significant sources of uncertainty, and all relevant sources of information.
- Faithfulness: our uncertainty report should accurately describe what we take the uncertainty to be.

PHILOSOPHICAL TRANSACTIONS A

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Research

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climatology

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False precision, surprise and improved uncertainty assessment

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An uncertainty report describes the extent of an agent's uncertainty about some matter. We identify two basic requirements for uncertainty reports, which we call *faithfulness* and *completeness*. We then discuss two pitfalls of uncertainty assessment that often result in reports that fail to meet these requirements. The first involves adopting a one-size-fits-all approach to the representation of uncertainty, while the second involves failing to take account of the risk of surprises. In connection with the latter, we respond to the objection that it is impossible to account for the risk of genuine surprises. After outlining some steps that both scientists and the bodies who commission uncertainty assessments can take to help avoid these pitfalls, we explain why striving for faithfulness and completeness is important.

1. Introduction

Many questions of interest to decision-makers are empirical questions that science can help to answer. Do levels of air pollution in our region regularly exceed target levels? What causes such elevated pollution levels? What are the health consequences? Though answers to empirical questions like these are never logically certain, in some cases the uncertainty is negligible; the answers are beyond any reasonable doubt and can be

Summing up

KEY POINTS

1. What is uncertainty?
   - *There are different conceptions of uncertainty: error view, epistemic view, hybrid views…*
2. The importance of uncertainty assessment
   - *Uncertainty information is essential if we are to be able to draw conclusions from data / modeling results.*
3. Uncertainty models and budgets
   - *Uncertainty budgets/models are tools that can help to structure the assessment of uncertainty.*
4. The quality of uncertainty estimates
   - *Ideally, an uncertainty assessment rigorously accounts for all significant sources of uncertainty, but what matters in practice is that uncertainty information is adequate for the purposes at hand*.
5. The ethics of uncertainty assessment
   - *Sometimes, misrepresenting uncertainty can be highly consequential; faithfulness and completeness are two basic criteria for consequential UQ.*

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