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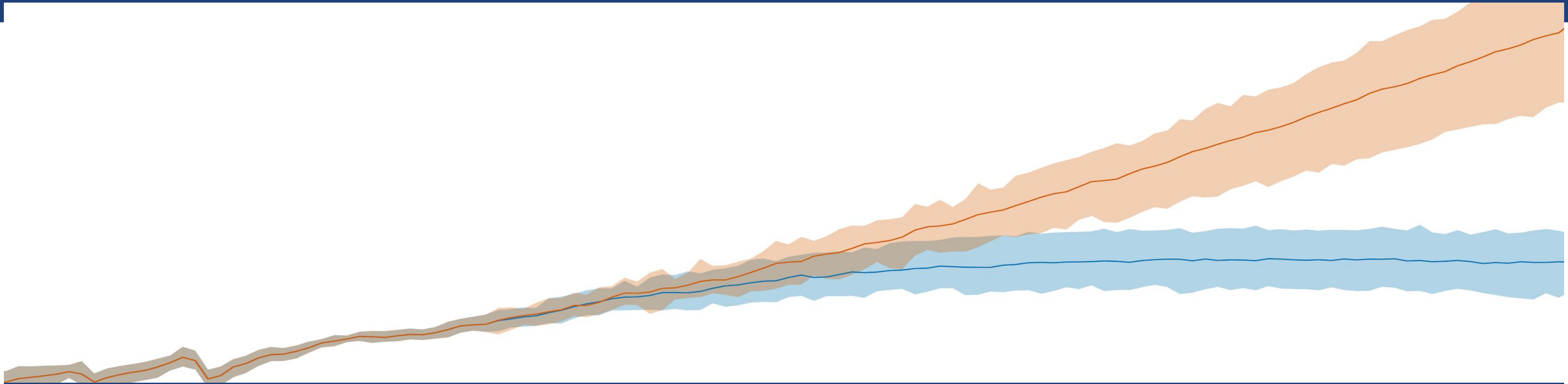

Uncertainties in multi-model assessments of future climate

Lukas Brunner (ETH Zurich) | Virtual EC-Earth meeting | November 16th 2021

With contributions from Reto Knutti, Ruth Lorenz, Angeline G. Pendergrass, Flavio Lehner, Anna L. Merrifield and many others

A very brief history of model comparison

- 1996/1997: **CMIP1** and **CMIP2** compare the ability of coupled climate models to simulate stable and warming climate Meehl et al. (1997), Meehl et al. (2000)
- 2005: **CMIP3** provides historical and future scenario runs Meehl et al. (2005)
- Early 2000s: Increasing number of studies using properties emerging from multi-model comparisons Knutti et al. (2002), Stott and Kettleborough (2002), Tebaldi et al (2005), Furrer et al. (2007), Tebaldi and Knutti (2007), Meehl et al. (2007)
- 2010: **CMIP5** includes about 50 models, specialized MIPs, prediction experiments Taylor et al. (2012)
- 2020: With **CMIP6** the most comprehensive comparison so far starts becoming available Eyring et al (2016)

An output-based view on ~25 years of model development

Generalized model-observations distances

- model performance reduced to only 2 variables
  - 20-year climatology of temperature (1981-1999)*
  - 20-year climatology of precipitation (1981-1999)*
- difference to ERA5 on a grid cell level (2.5°x2.5°)
  - global mean bias removed before difference
- Area-weighted root-mean-squared distance

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*last 20 years of pre-industrial control for CMIP2

EC-Earth in CMIP 5 & 6

- One of the best models in CMIP5
- Distance to observations stayed about the same from CMIP 6 to 5
  → average model in CMIP6
- very large 20-year internal variability
  - mainly due to temperature in high northern latitudes
  - similar for 50- and 165-year internal variability

→ Oscillation between low/high AMOC with a period of about 200 years. Döscher et al. (2021, in press)

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Model development & dependence

- The CMIPs try to collect as many models as possible (**'ensembles of opportunity'**) Tebaldi and Knutti (2007)
  - Models that share components or ideas
  - Models that have been branched from each other
  - Different versions of the same model
- Giving each model one vote when **assessing future climate** does not account for this **model dependence**
- Strategies beyond such a **'model democracy'**
  - **Model independence weighting** Sanderson et al. (2015)
  - Institutional democracy Leduc et al. (2016)
  - Pooling models by components Maher et al. (2021)

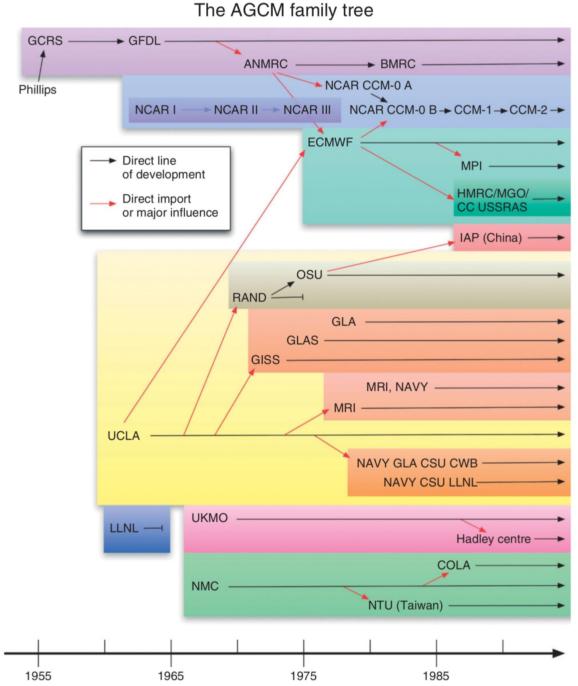

Figure: Development and dependencies for several climate models. Edwards (2010)

An output-based view on model dependence

Generalized model-model distances visualized as a tree based on hierarchical clustering

- same setup as for observation distances
  - climatology of temperature and precipitation
  - bias-corrected global fields
- models with know and clear connections are labeled in the same color
- CMIP6 models (**bold font**) and selected CMIP5 models (normal font)
  - NCAR/CESM, HadGEM, and EC-Earth families

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Uncertainty in multi-model projections of future change

3 main sources are typically considered Hawkins and Sutton (2009)

- **Scenario uncertainty** representing different socio-economic and technological developments
- **Model uncertainty** based on structural differences between models in a multi-model ensemble
- **Internal variability** due to the chaotic behavior of the climate system

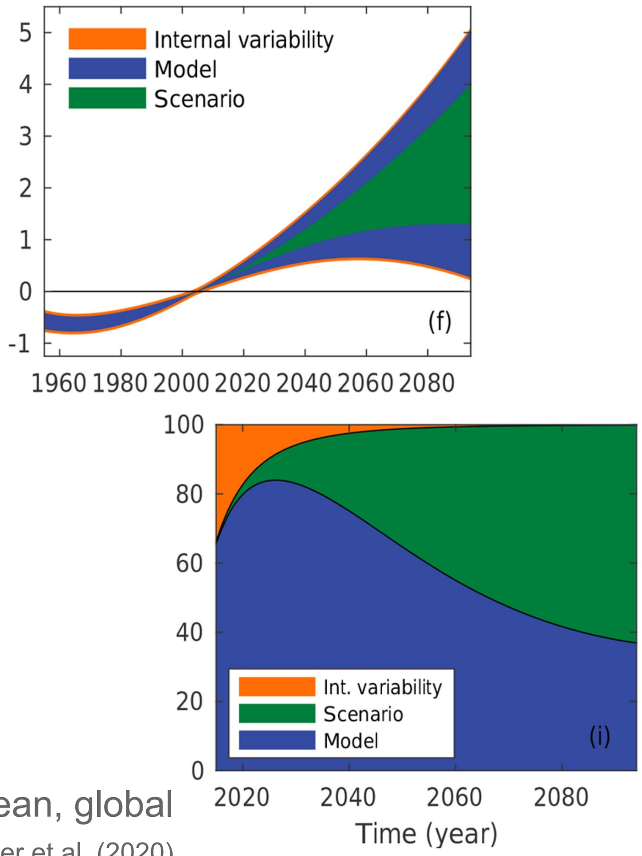


Figure: Uncertainty in decadal mean, global mean temperature from CMIP6. Lehner et al. (2020)

On the interpretation of model uncertainty

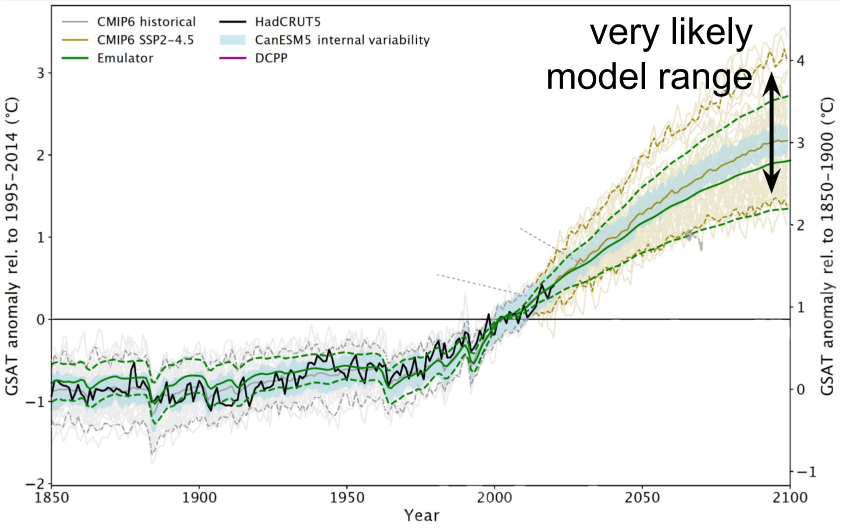


Figure: Global mean, annual mean temperature change based on 39 CMIP6 models. The dashed brown lines indicate the 90% model range. Adapted from IPCC AR6

On the interpretation of model uncertainty

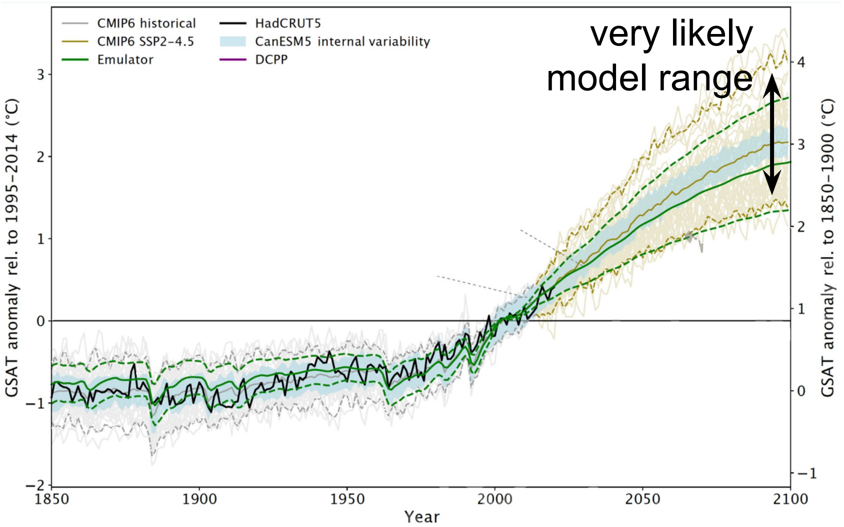
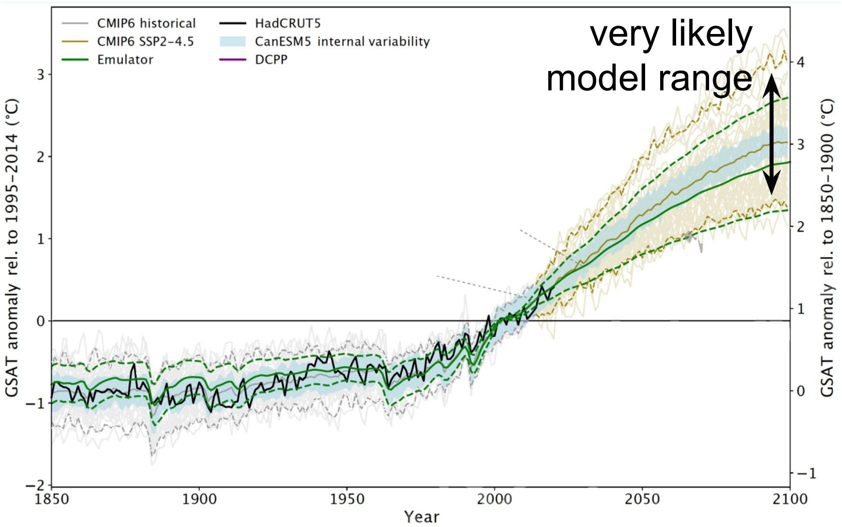


Figure: Global mean, annual mean temperature change based on 39 CMIP6 models. **The dashed brown lines indicate the 90% model range which is interpreted as the 66% (likely) uncertainty range.** Adapted from IPCC AR6

The **actual uncertainty might be larger** than the raw model uncertainty

- There might be processes not covered by any model IPCC AR5, IPCC AR6

On the interpretation of model uncertainty



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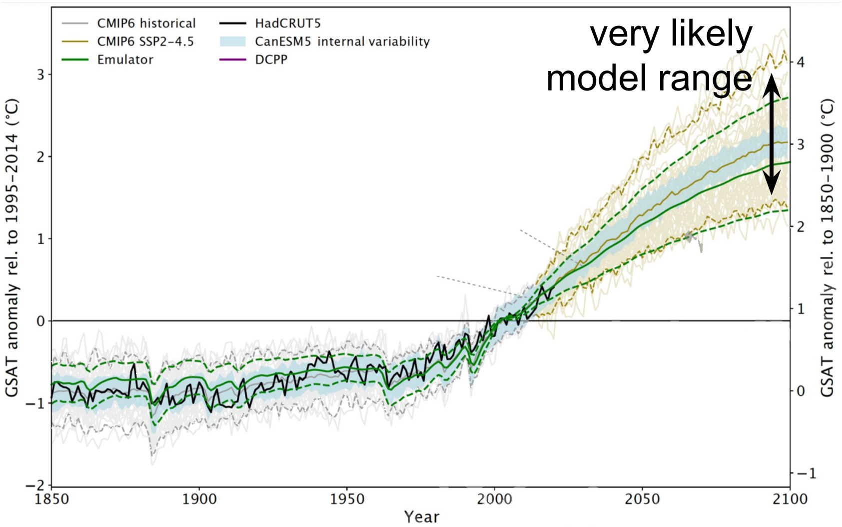
The **actual uncertainty might be smaller** than the raw model uncertainty

- Not all models are equally **'fit for purpose'** Sanderson et al. (2015), Herger et al. (2018)

On the interpretation of model uncertainty



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Weighting models by independence and performance

$$w_i = \frac{e^{-\frac{D_i^2}{\sigma_D^2}}}{1 + \sum_{j \neq i}^{M} \left(e^{-\frac{S_{ij}^2}{\sigma_S^2}} \right)}$$

Knutti et al. (2017)

- w_i : weight for model i
- D_i : generalised distance of model i to observations (performance diagnostics)
- σ_D : performance shape parameter
- M: number of models
- S_{ij} : generalised distance between model pair (independence diagnostics)
- σ_S : independence shape parameter

Effect of weighting global mean temperature from CMIP6

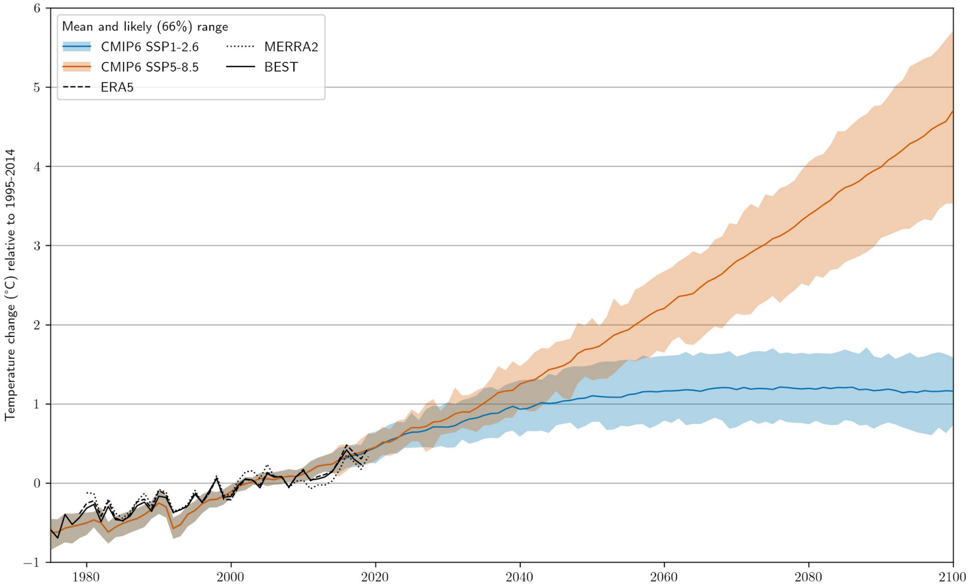


Figure: Global mean, annual mean temperature change (relative to 1995-2014) from 33 CMIP6. Brunner et al. (2020a)

Effect of weighting global mean temperature from CMIP6

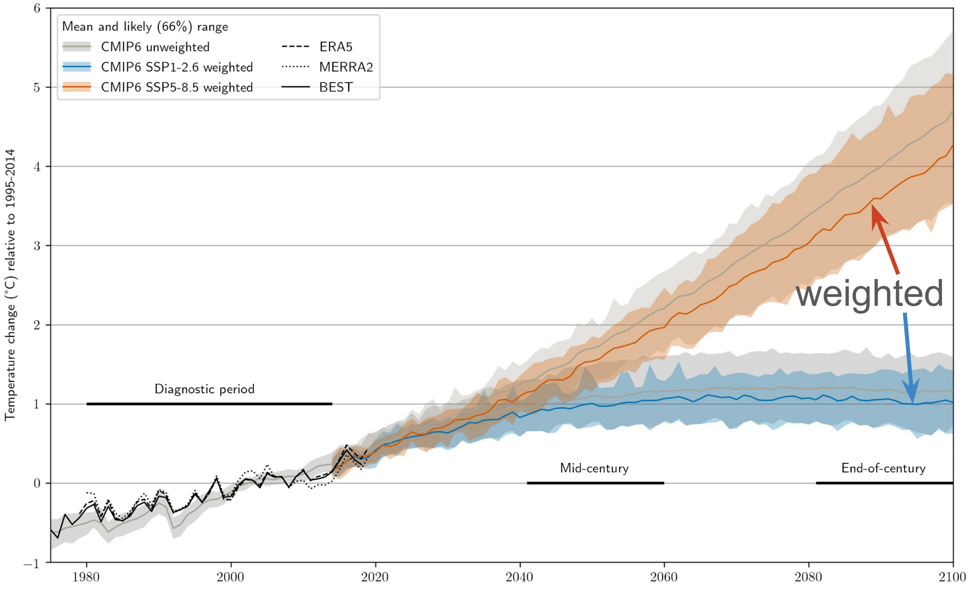


Figure: Weighted global mean, annual mean temperature change (relative to 1995-2014) from 33 CMIP6 models.
Brunner et al. (2020a)

- The weighted distribution shows **reduced mean warming from CMIP6** models consistent with other recent studies
  - Nijsse et al. (2020)
  - Tokarska et al. (2020)
  - Ribes et al. (2021)
- **Reduction of uncertainty** by 10%-20% for the likely range due to a constraining of the upper percentiles

Skill and reliability of weighting: model-as-truth testing

- Comparable to a **cross-validation** in statistics (also termed **perfect model test** or using models as **pseudo-observations**)
- **Caveat:** Can not account for processes not included in any of the models
- Model weighting is perfectly reliable by construction
- Projection **skill increases by 10%-20%** in the median depending on SSP and time period

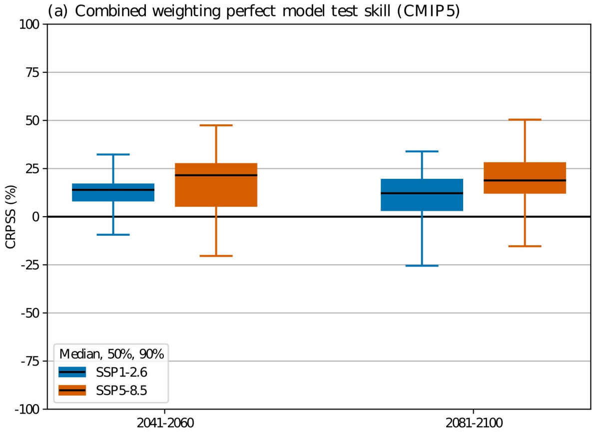


Figure: Continuous ranked probability skill score (CRPSS) for CMIP6 relative to the unweighted ensemble using perfect models from CMIP5.
Brunner et al. (2020a)

Consistency of weighting: comparison to other methods

For climate models CMIP provides a **coordinated framework** for comparison. This does not exist for constraining methods. **Differences in the results might have nothing to do with the methods**:

- variable (temperature vs precip)
- region (global vs Europe)
- season and time period
- models included
- uncertainties included
- ...

Figures: Comparing (top) methods and (right) apples and oranges right: CC-BY M. Johnson

A coordinated framework for method comparison

European Climate Prediction system

We brought together **8 groups** working on constraining and developed a **level playing field for method comparison**

2 conditions for participation:

1. quantify uncertainty in future projections
2. able to handle common settings

Institution name	Method acronym	Method name	References
ETH Zurich (Switzerland)	ClimWIP	Climate Model Weighting by Independence and Performance	Knutti et al. (2017b); Lorenz et al. (2018); Brunner et al. (2019)[a]
International Centre for Theoretical Physics (Italy)	REA	Reliability ensemble averaging	Giorgi and Mearns (2002, 2003)[b]
University of Edinburgh (United Kingdom)	ASK	Allen–Stott–Kettleborough	Allen et al. (2000); Stott and Kettleborough (2002); Kettleborough et al. (2007)
Centre National de Recherches Météorologiques (France)	HistC	Historically constrained probabilistic projections	Ribes et al. (2020, manus to *Sci. Adv.*)[c] now: KCC
Met Office (United Kingdom)	UKCP	U.K. Climate Projections (UKCP) Bayesian probabilistic projections method	Sexton et al. (2012); Harris et al. (2013); Sexton and Harris (2015); Murphy et al. (2018)
University of Oxford (United Kingdom)	CALL	Calibrated large ensemble projections	O'Reilly et al. (2020)
Royal Netherlands Meteorological Institute (Netherlands)	BNV*	Bootstrapped from natural variability	See the online supplemental material
Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (Italy)	ENA*	Ensemble analysis of probability distributions	See the online supplemental material

[a] Source code available online (https://github.com/lukasbrunner/ClimWIP).
[b] Source code available online (http://doi.org/10.5281/zenodo.3890966).
[c] Method tool available online (https://saidqasmi.shinyapps.io/bayesian).

Table: Participating institutions, methods, and references. Brunner et al. (2020b)

Comparing constrained European temperature change

- Trade-off between number of methods and the **fairness of the comparison**
- **Fairest** comparison: **4/8 methods** could participate
- All methods **narrow the uncertainty** range
- All methods agree on slightly **less warming**

→ not all cases look that nice

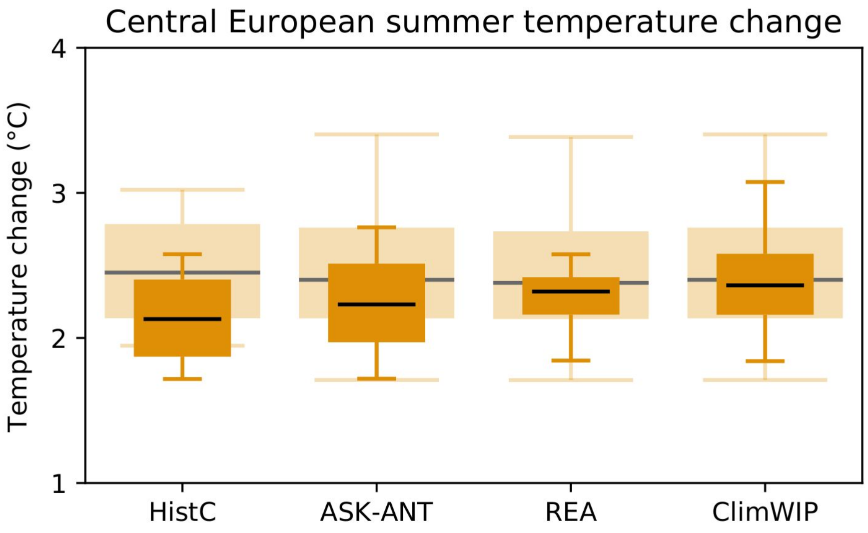
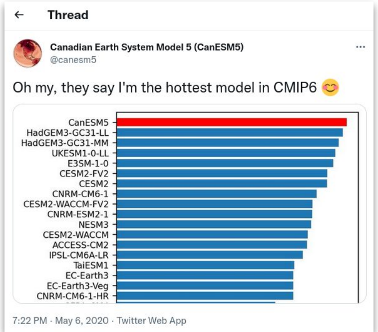
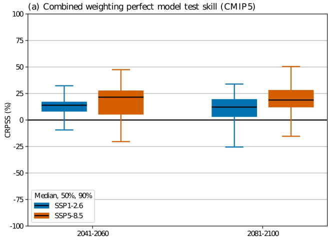


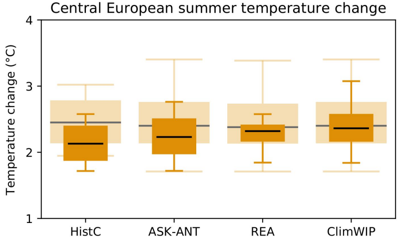
Figure: Unconstrained (light) and constrained (dark) Central European summer temperature change (2041-60 relative to 1995-2014) from CMIP5. Brunner et al. (2020b)

Summary and conclusions

- CMIP multi-model ensembles allow a **consistent comparison of models**
- The use of such multi-model ensembles leads to **model uncertainty**
- To **better quantify model uncertainty** methods have been developed to account, e.g., for past model performance
- **Model-as-truth tests** can be important to verify the **skill** of such methods
- A framework for a **consistent comparison of constraining methods** can help to check consistency between them







Thank you!

Question?

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