Model Structure and Climate Data Uncertainty in Historical Simulations of the Terrestrial Carbon Cycle (1850-2014)

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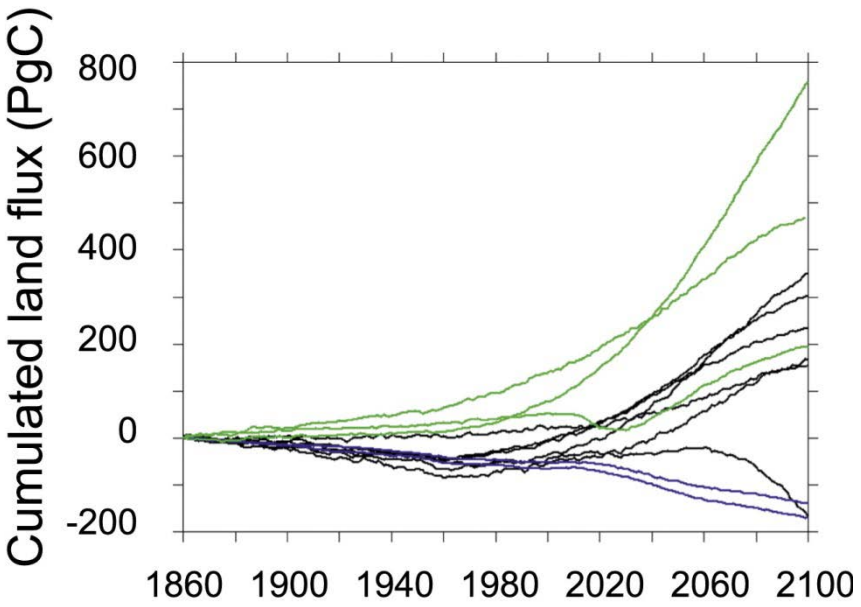
CMIP5 carbon cycle projections



11 Earth system models with RCP8.5

Large uncertainty in cumulative land uptake

Much interest in how to reduce uncertainty

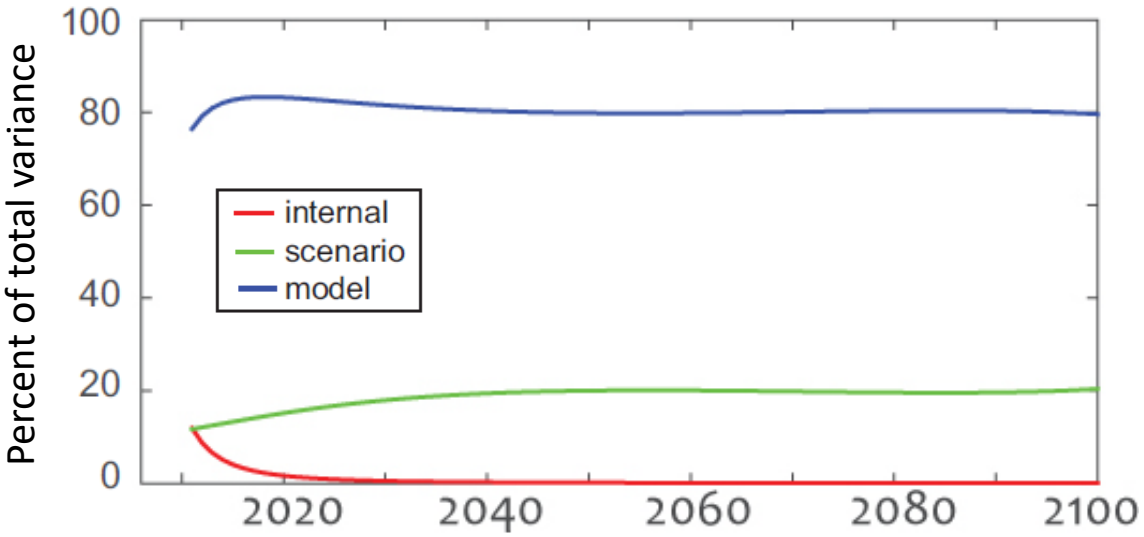
Friedlingstein et al. (2014) *J. Clim.*, 27, 511-526

CMIP5 model uncertainty

Sources of uncertainty

- Internal variability
- Model structure
- Scenarios

Hawkins & Sutton (2009) *BAMS*, 90, 1095-1107



Lovenduski & Bonan (2017) *Environ. Res. Lett.*, 12, 044020

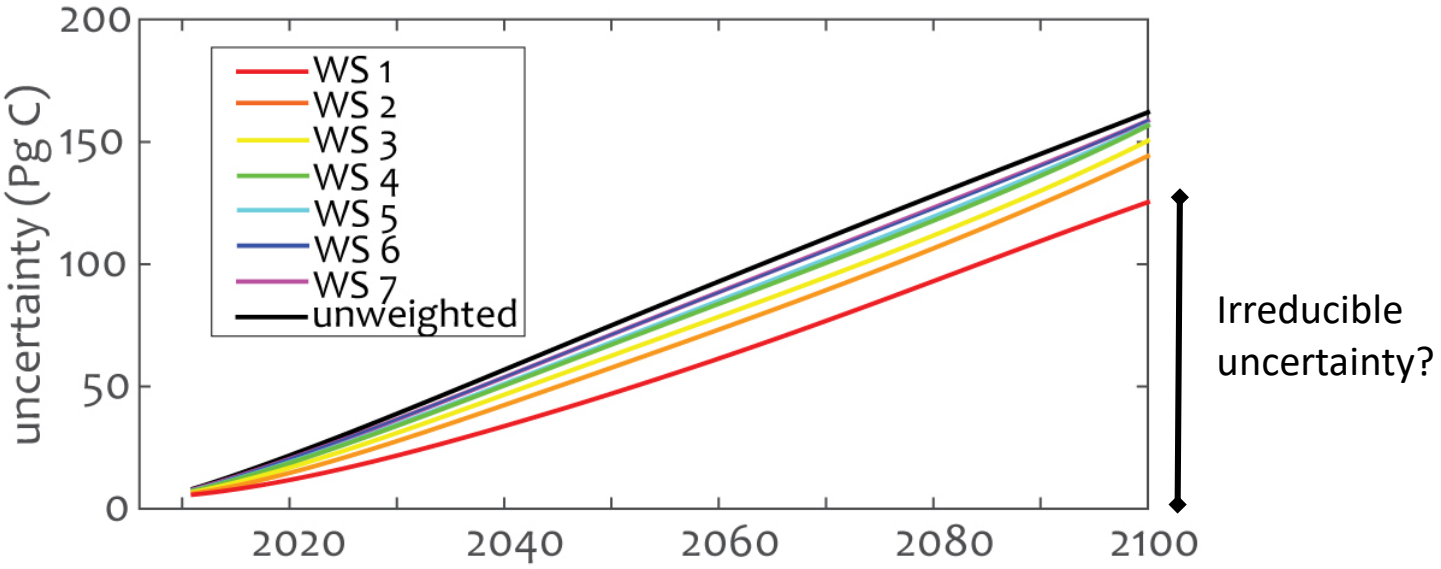
Much research to reduce uncertainty

- Better biogeochemical process representation
- Parameter estimation

But what about climate forcing uncertainty?

CMIP5 model uncertainty

Weighting models does not substantially reduce uncertainty



Lovenduski & Bonan (2017) *Environ. Res. Lett.*, 12, 044020

Much research to reduce uncertainty

- Better biogeochemical process representation
- Parameter estimation

But what about climate forcing uncertainty?

Ensemble of land-only CLM historical simulations

3 models × 2 climates

Model	
CLM4	Strong N downregulation of GPP; low soil C
CLM4.5	Improved GPP and vertically-resolved soil C
CLM5	Flexible plant C:N; optimal canopy N; cost of N uptake

Poleward shift in C
Less sensitive to N addition
Higher CO_2 fertilization

(Will Wieder, NCAR)

Climate	
CRUNCEP	GCP, Trendy
GSWP3	CMIP6: LUMIP, LS3MIP

Use analysis of variance to examine the contribution of model structure and climate forcing to carbon cycle uncertainty

Uncertainty partitioning

Between group variation

Within group variation

	Climate	
Model	GSWP3	CRUNCEP
CLM4	x_{11}	x_{12}
CLM4.5	x_{21}	x_{22}
CLM5	x_{31}	x_{32}
Mean	$x_{.1}$	$x_{.2}$
Variance	s^2_1	s^2_2

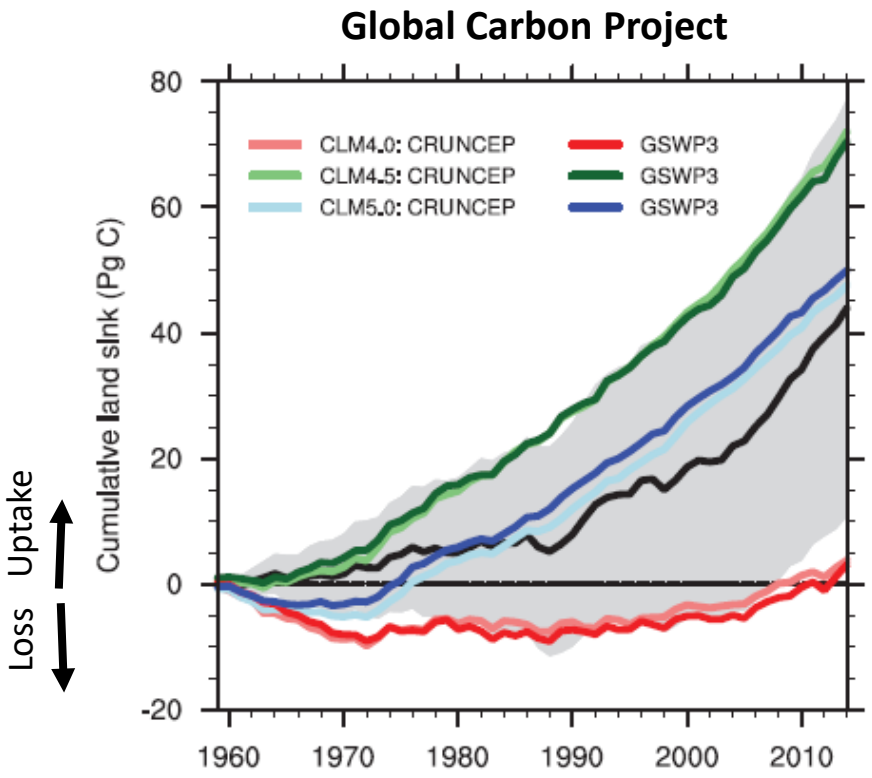
Total uncertainty
Variance across the 6-member ensemble

Climate uncertainty
Variance of the GSWP3 and CRUNCEP multi-model means ($x_{.1}$, $x_{.2}$)

Model uncertainty
Average of the multi-model variances for GSWP3 and CRUNCEP (s^2_1, s^2_2)

This is equivalent to a fixed-effects single factor analysis of variance for k=2 groups with n=3 within each group

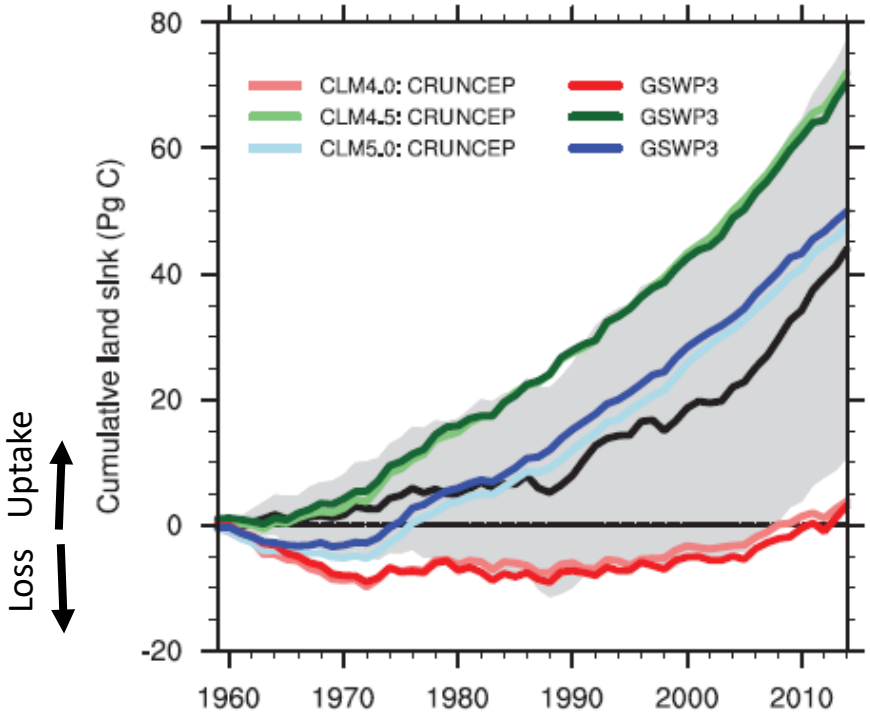
Cumulative net biome production



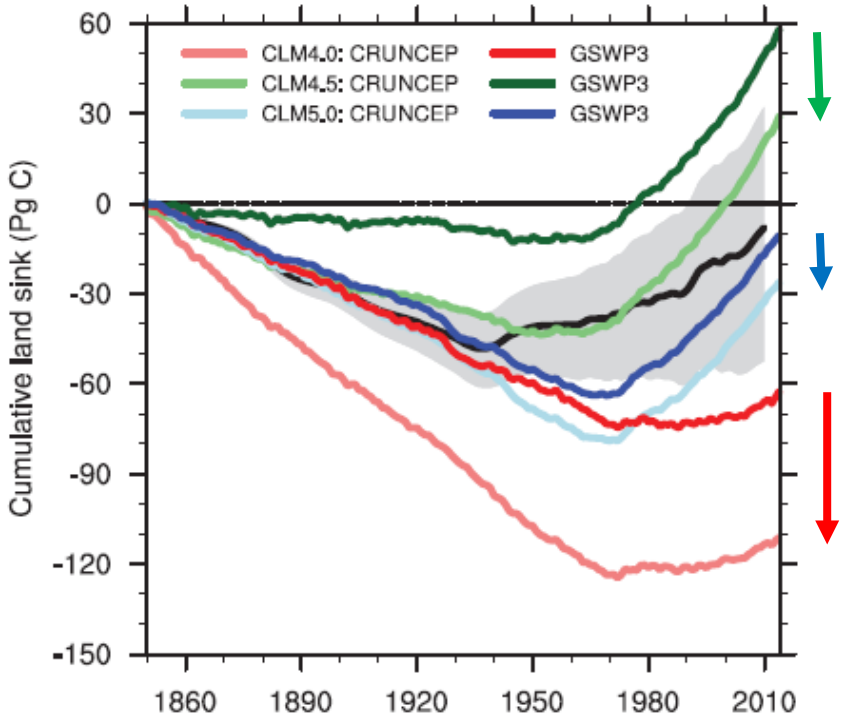
- CLM5 is improved compared with other models
- Climate is less important than model differences
- But all models within GCP uncertainty

Cumulative net biome production

Global Carbon Project

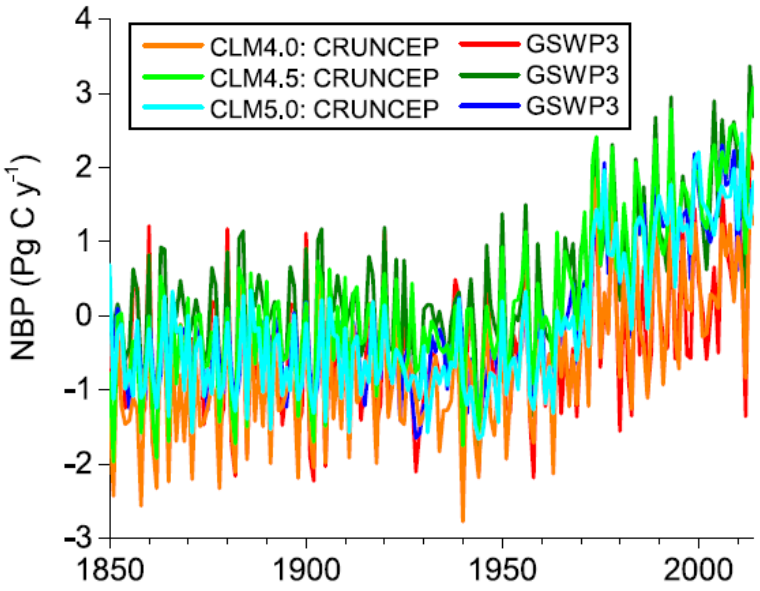


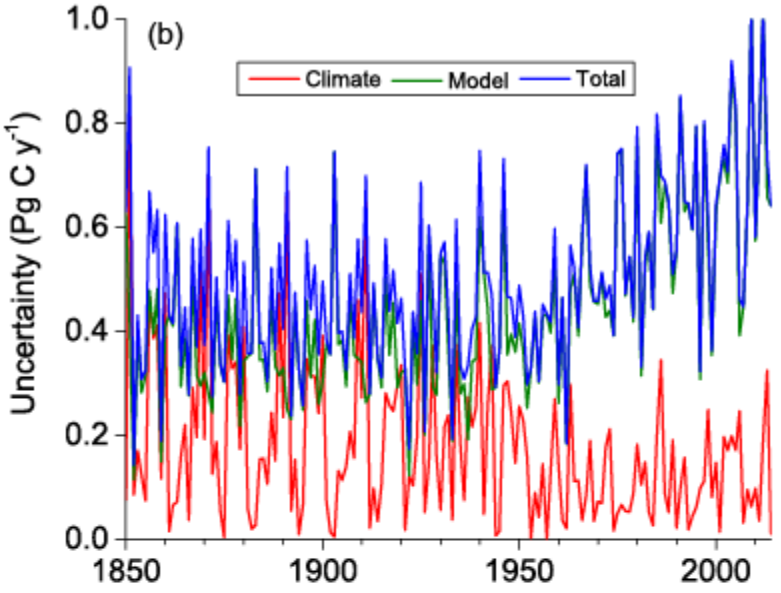
Hoffman

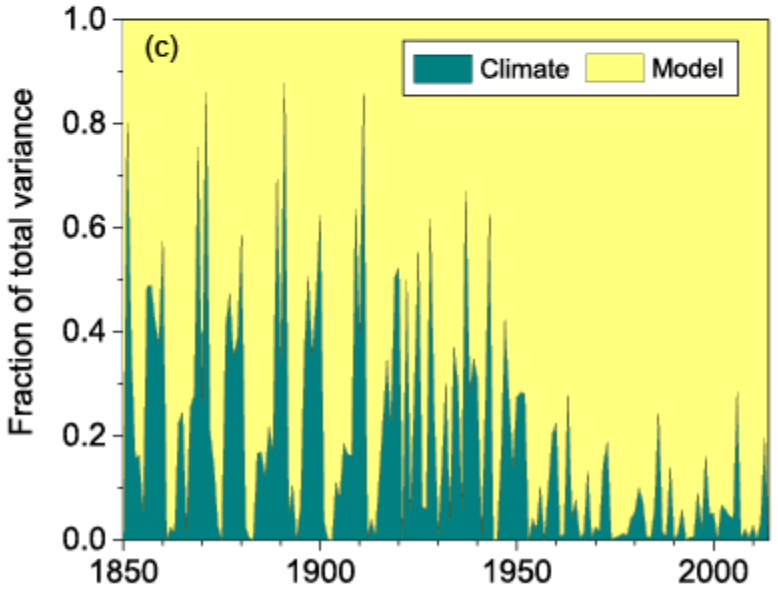


- CRUNCEP reduces land sink compared with GSWP3
- CLM4.5 (CRUNCEP) and CLM5 (GSWP3) are equally “good” and within uncertainty

NBP uncertainty

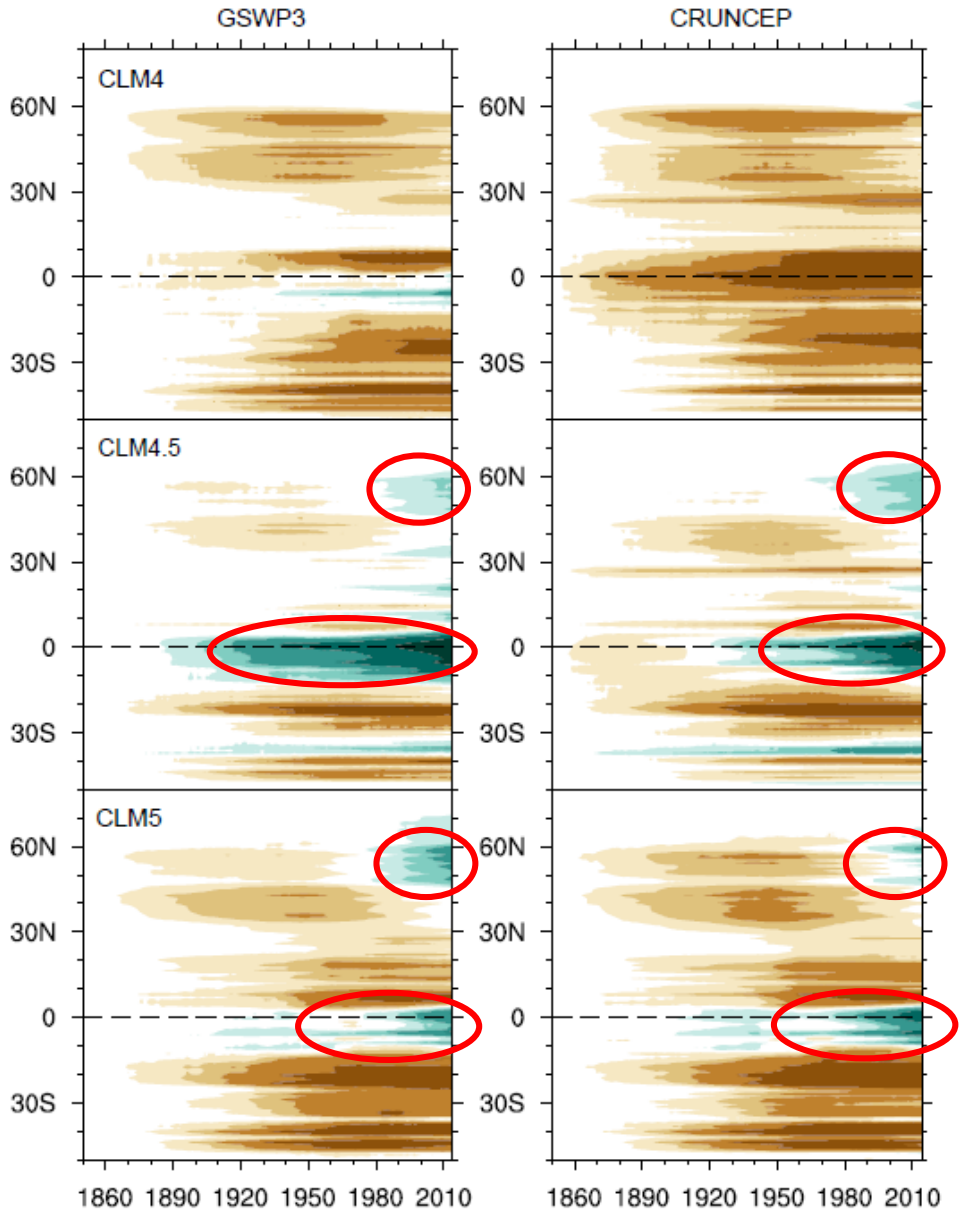


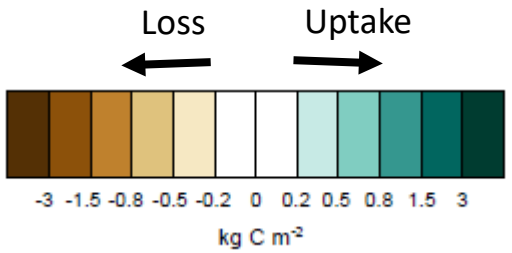




Large climate uncertainty prior to about 1950s, but individual years have considerable climate uncertainty (20% or more of total) in the 1980s-2010s

Cumulative net biome production





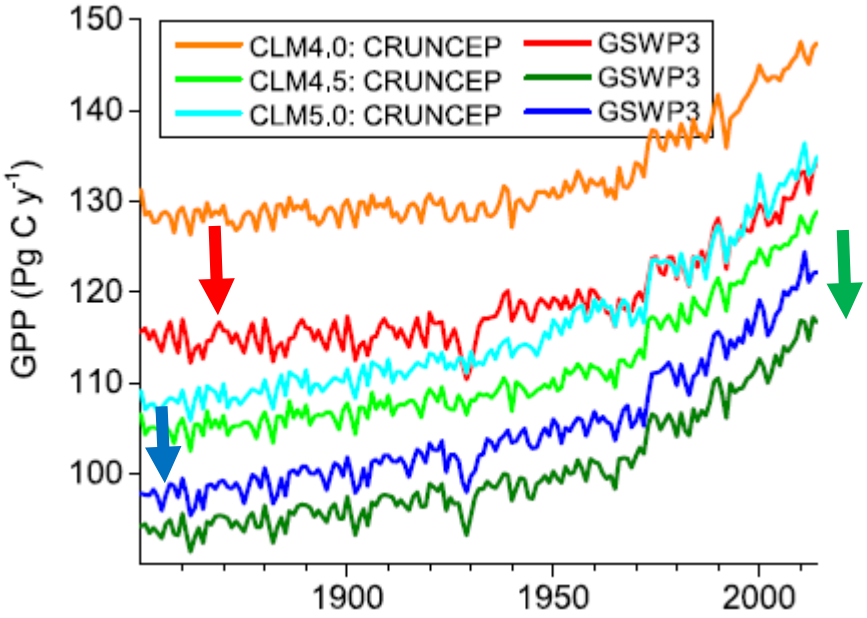
CLM4.5

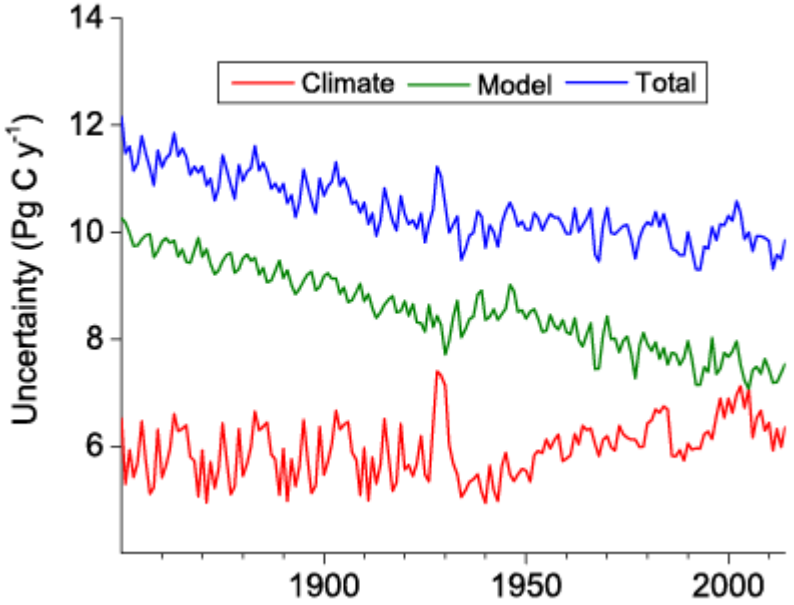
- Strong tropical sink (weaker with CRUNCEP)
- Weak northern sink (stronger with CRUNCEP)

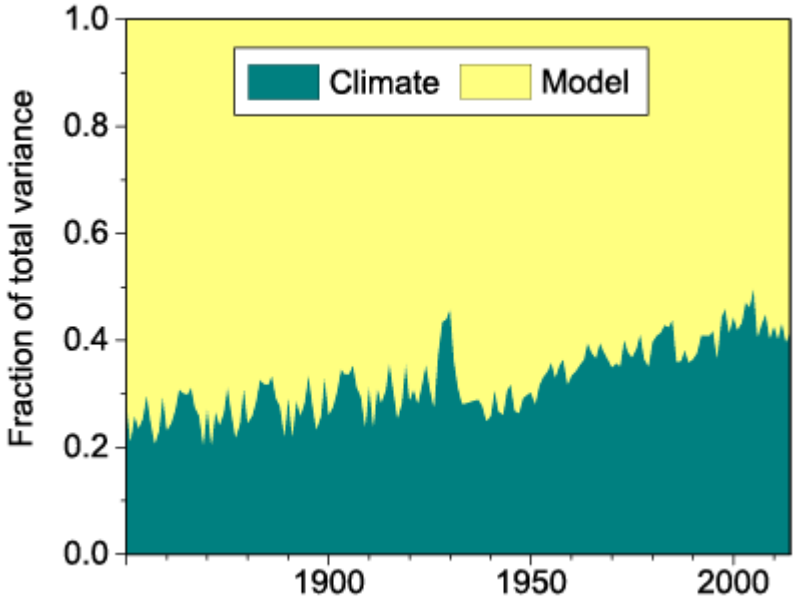
CLM5

- Weaker tropical sink (stronger for CRUNCEP)
- Northern sink (stronger for GSWP3)

GPP uncertainty

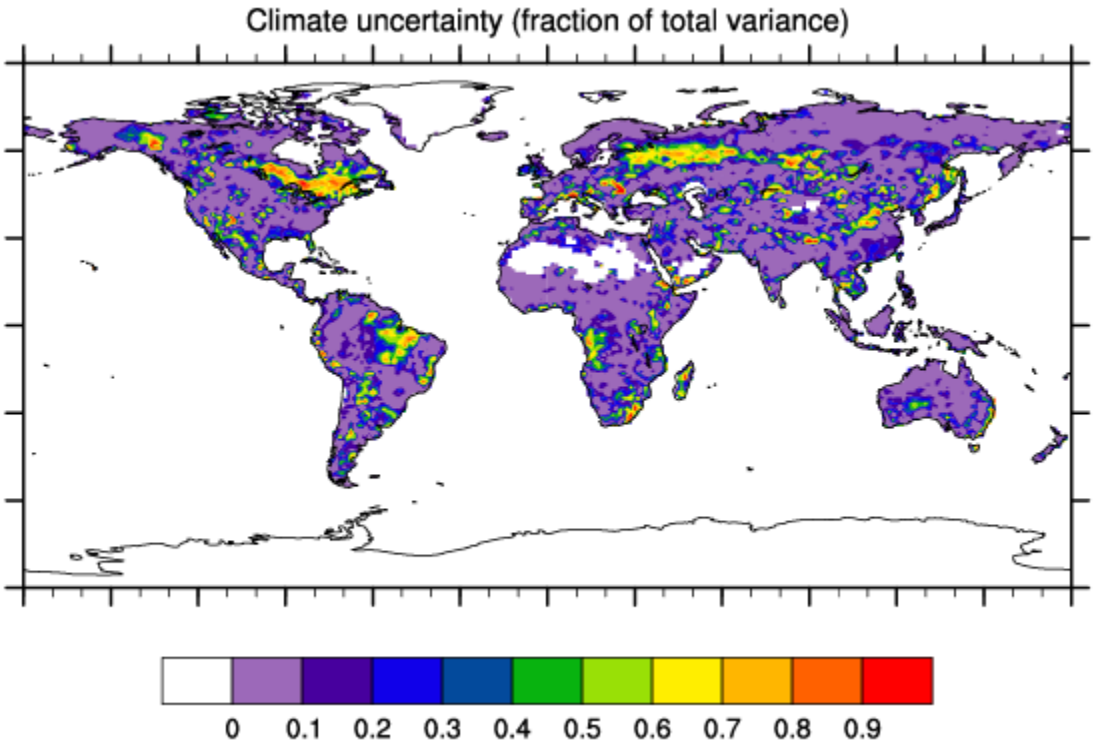






- GSWP3 reduces GPP compared with CRUNCEP
- Climate uncertainty is a substantial contribution to total uncertainty
- Similar results for NPP, HR, VEGC, SOMC

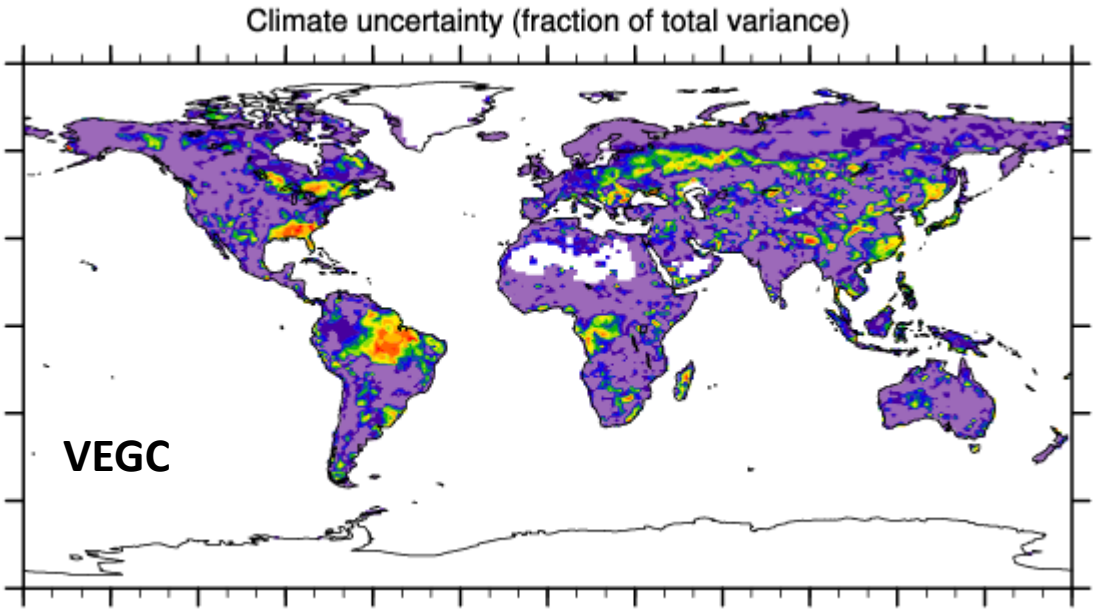
GPP uncertainty (2000-2009)

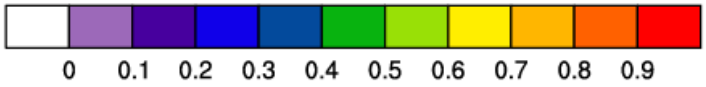


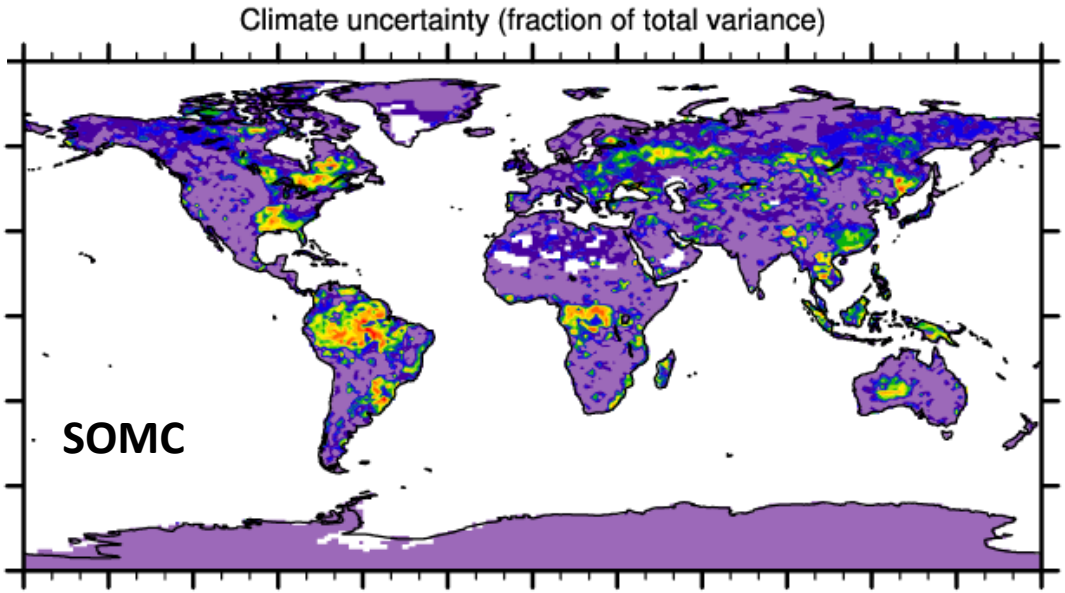
Climate uncertainty can be regionally large, most prominently in boreal North America and Eurasia and in eastern Amazonia and western equatorial Africa where climate uncertainty exceeds 60% of total uncertainty

Similar results for NPP, HR, VEGC, SOMC

Carbon uncertainty (2000-2009)



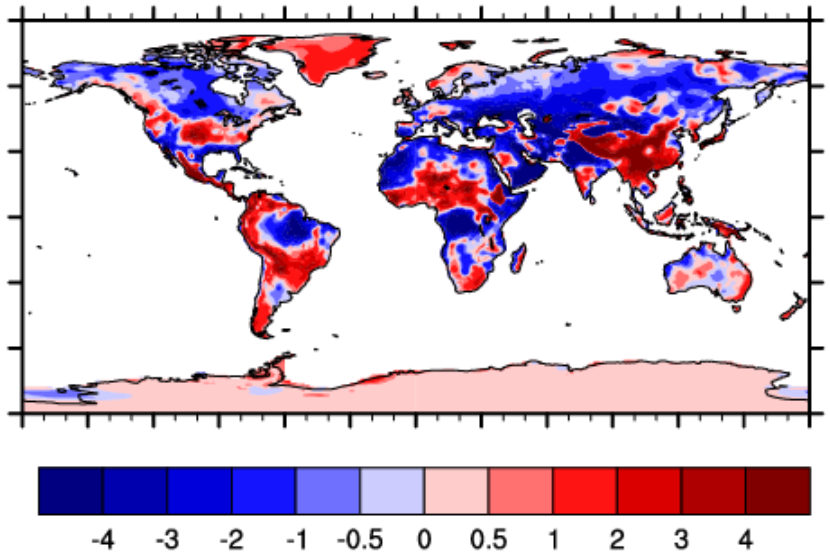




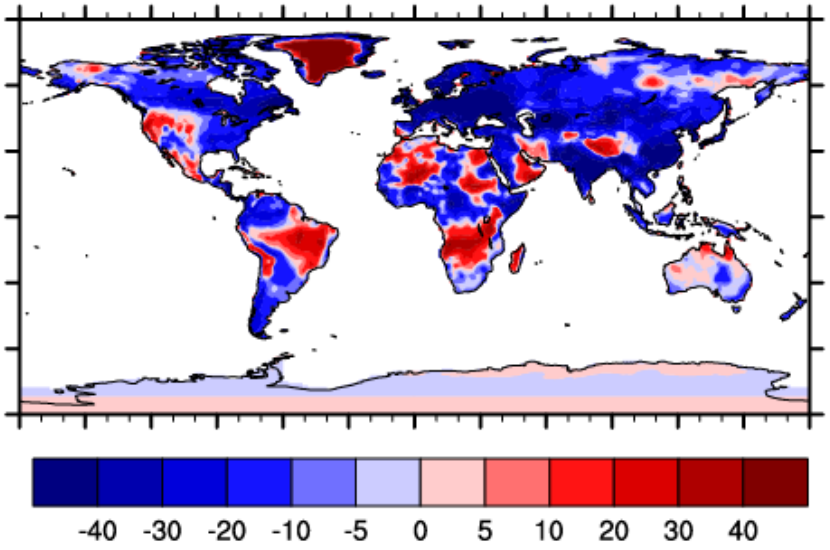
Climate differences (2000-2009)

JJA (GSWP3 – CRUNCEP)

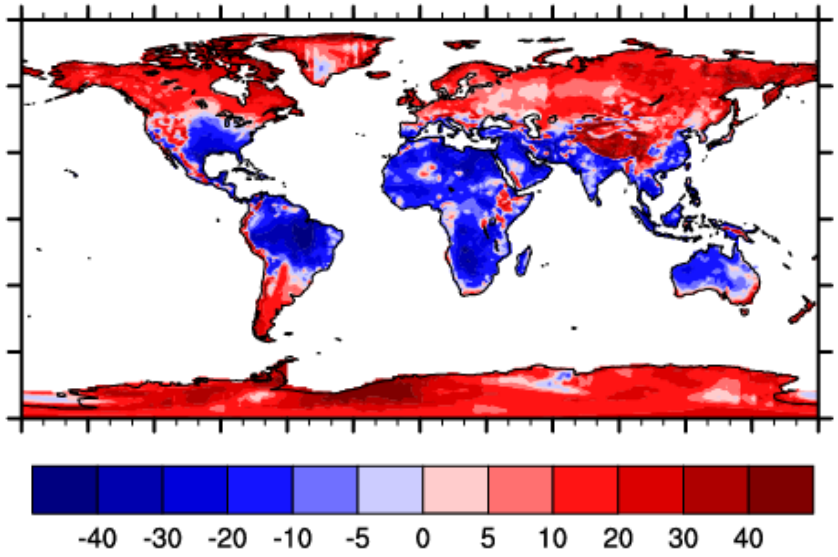
Specific humidity (g kg^{-1})



Solar radiation (W m^{-2})

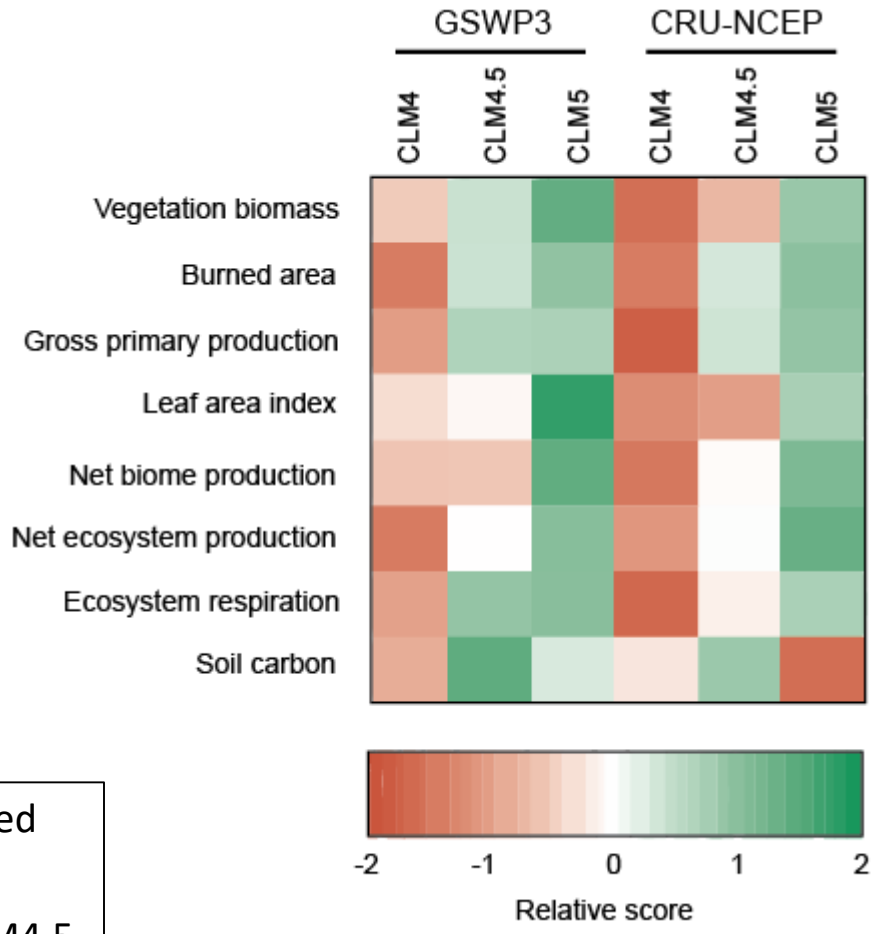


Longwave radiation (W m^{-2})



ILAMB benchmarking

Is any one simulation “best”?

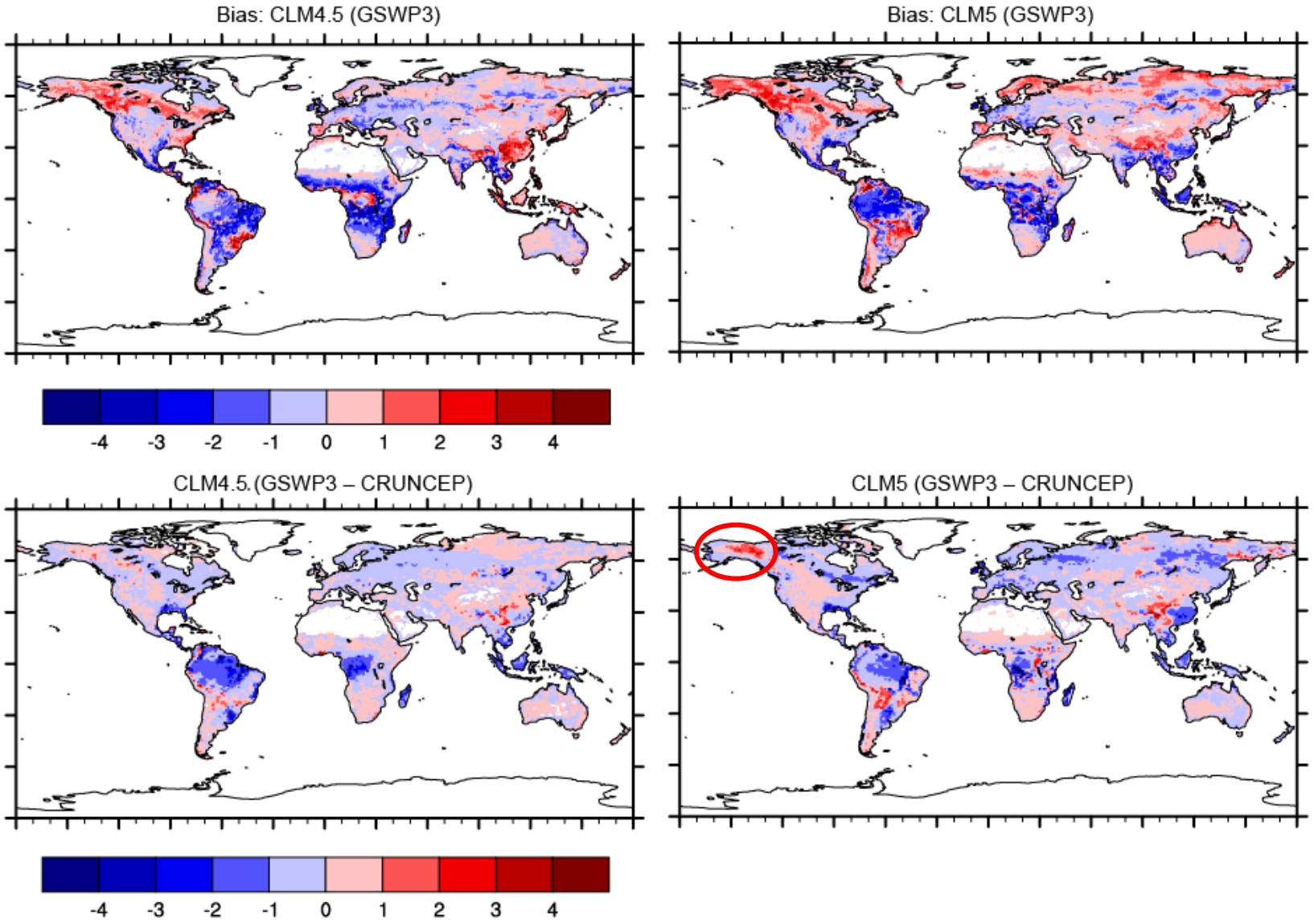


- CLM4 is prominently deficient compared with CLM4.5 and CLM5
- CLM5 is better (darker green) than CLM4.5 and GSWP3 is better (darker green) than CRUNCEP in many metrics, or are the simulations just “different”?

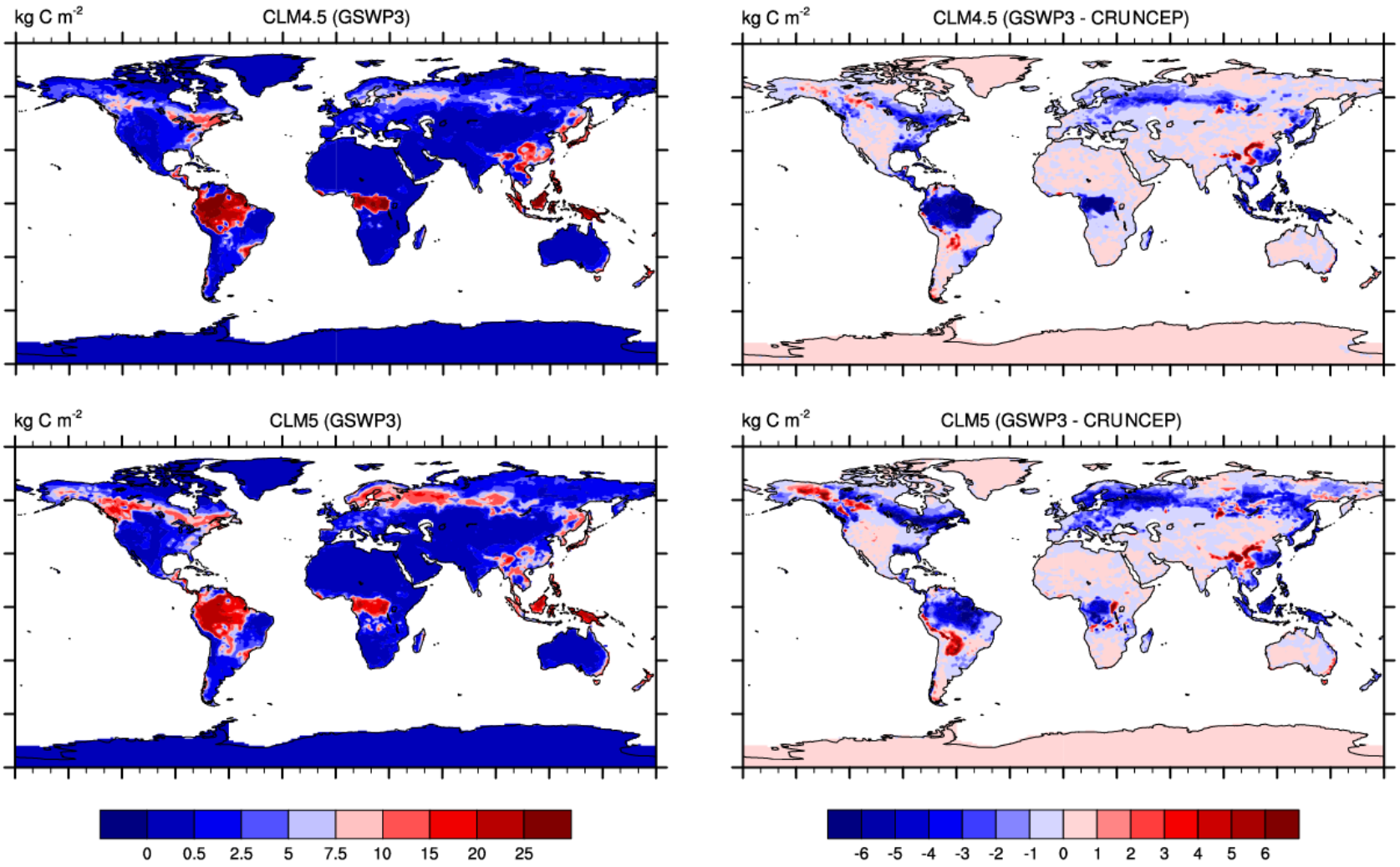
Green = better
Red = worse

ILAMB benchmarking (GPP)

Annual GPP (g C m^{-2} day^{-1})



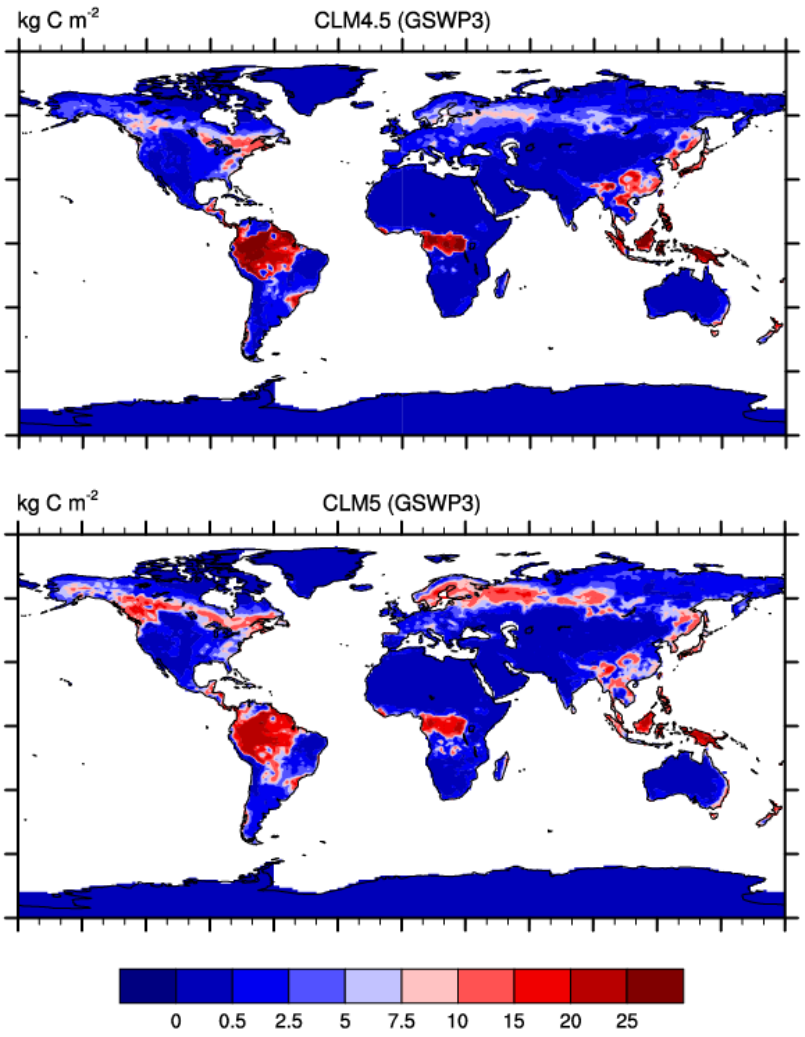
ILAMB benchmarking (VEGC)



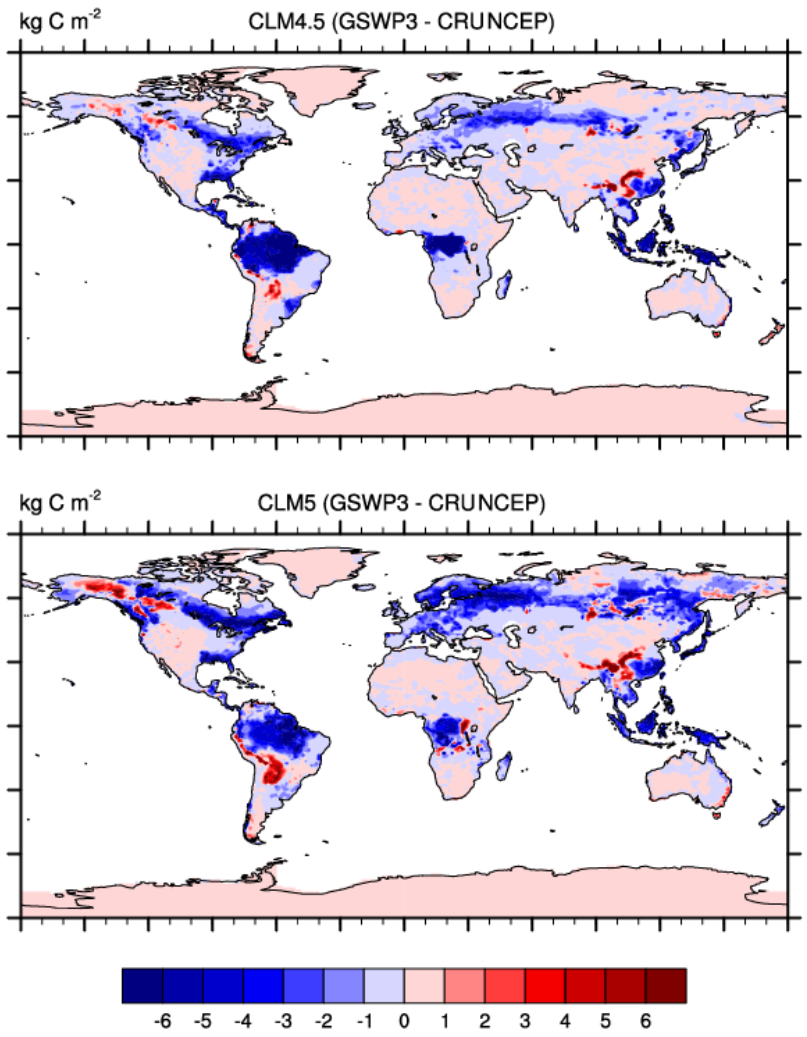
- CLM4.5 and CLM5 are biased high in boreal North America and Eurasia
- CLM5 enhances the positive bias (high GPP)

GSWP3 reduces VEGC (except Alaska and NW Canada)

ILAMB benchmarking (VEGC)

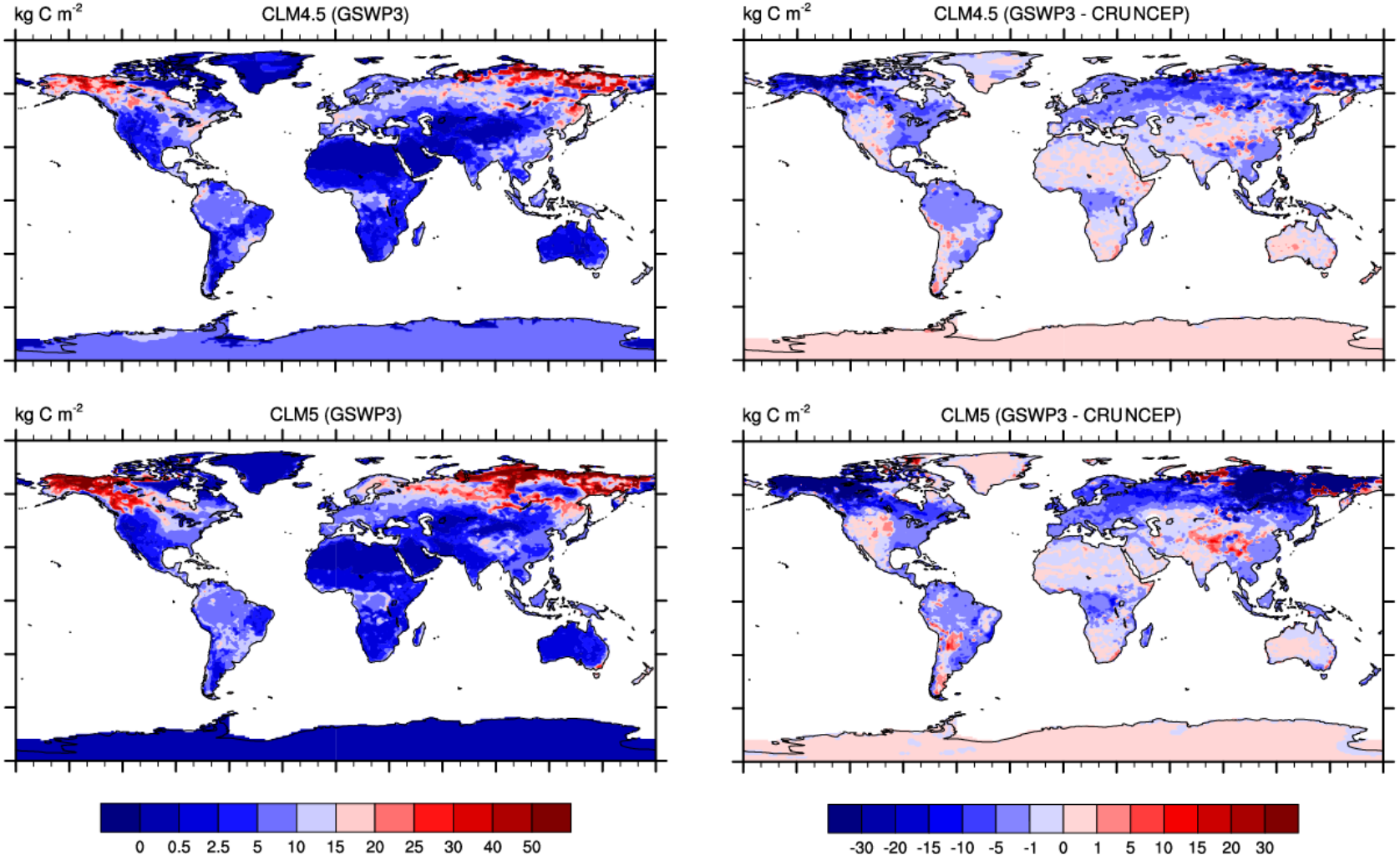


CLM5 reduces the positive tropical biomass bias (low GPP)



GSWP3 reduces the tropical bias compared with CRUNCEP

ILAMB benchmarking (SOMC)



CLM5: more SOMC compared with CLM4.5

Less SOMC for GSWP3 compared with CRUNCEP

ILAMB benchmarking (SOMC)

ILAMB scores for soil carbon (SOMC)
in comparison with NCSCD

Simulation	Bias	Spatial distribution	Overall
GSWP3			
CLM4	0.44	0.15	0.29
CLM4.5	0.56	0.82	0.69
CLM5	0.53	0.64	0.59
CRUNCEP			
CLM4	0.46	0.21	0.34
CLM4.5	0.57	0.77	0.67
CLM5	0.43	0.19	0.31

Concluding thoughts

Many studies have identified model structural uncertainty arising from process parameterizations and parameter values

The current study highlights the importance of climate forcing in generating carbon cycle uncertainty, *even when the models are forced with best-estimate climate reconstructions over the industrial era*

In a full ESM, climate uncertainty is likely even larger

Models differ in their sensitivity to climate forcing; CLM5 has large climate sensitivity

We do not yet have a complete understanding of the sources of carbon cycle uncertainty

The conceptualization of uncertainty arising from this study implies embracing multiple feasible model simulations rather than focusing on which model or which simulation is best