PMIP3/CMIP5 Last Millennium Model Simulation Effort

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Paleoclimate Modelling Intercomparison Project 3

NCAR

Outline

- Background to the last millennium simulations in IPCC and PMIP
- Overview of experimental design for PMIP3 − CMIP5
- PMIP3 − CMIP5 simulations
- Other modeling efforts
- Next steps: CMIP6 and next PMIP

IPCC Working Group Fourth Assessment Report (AR4)

- Last Millennium (LM) simulations were an ‘ensemble of opportunity

Table 6.2. *Climate model simulations shown in Figure 6.13.*

Series	Model[a]	Model type	Forcings[b]	Reference
GSZ2003	ECHO-G	GCM	SV -G - - - -	González-Rouco et al., 2003
ORB2006	ECHO-G/MAGICC	GCM adj. using EBM[c]	SV -G -A -Z	Osborn et al., 2006
TBC..2006	HadCM3	GCM	SVOG -ALZ	Tett et al., 2007
AJS..2006	NCAR CSM	GCM	SV -G -A -Z	Mann et al., 2005b
BLC..2002	MoBiDiC	EMIC	SV -G -AL -	Bertrand et al., 2002b
CBK..2003	-	EBM[c]	SV -G -A - -	Crowley et al., 2003
GRT..2005	ECBilt-CLIO	EMIC	SV -G -A - -	Goosse et al., 2005b
GJB..2003	Bern CC	EBM[c]	SV -G -A -Z	Gerber et al., 2003
B..03-14C	Climber2	EMIC (solar from ^{14}C)	SV - -C -L -	Bauer et al., 2003
B..03-10Be	Climber2	EMIC (solar from ^{10}Be)	SV - -C -L -	Bauer et al., 2003
GBZ..2006	ECHO-G	GCM	SV -G - - - -	González-Rouco et al., 2006
SMC2006	ECHAM4/OPYC3	GCM	SV -G -A -Z	Stendel et al., 2006

Notes:

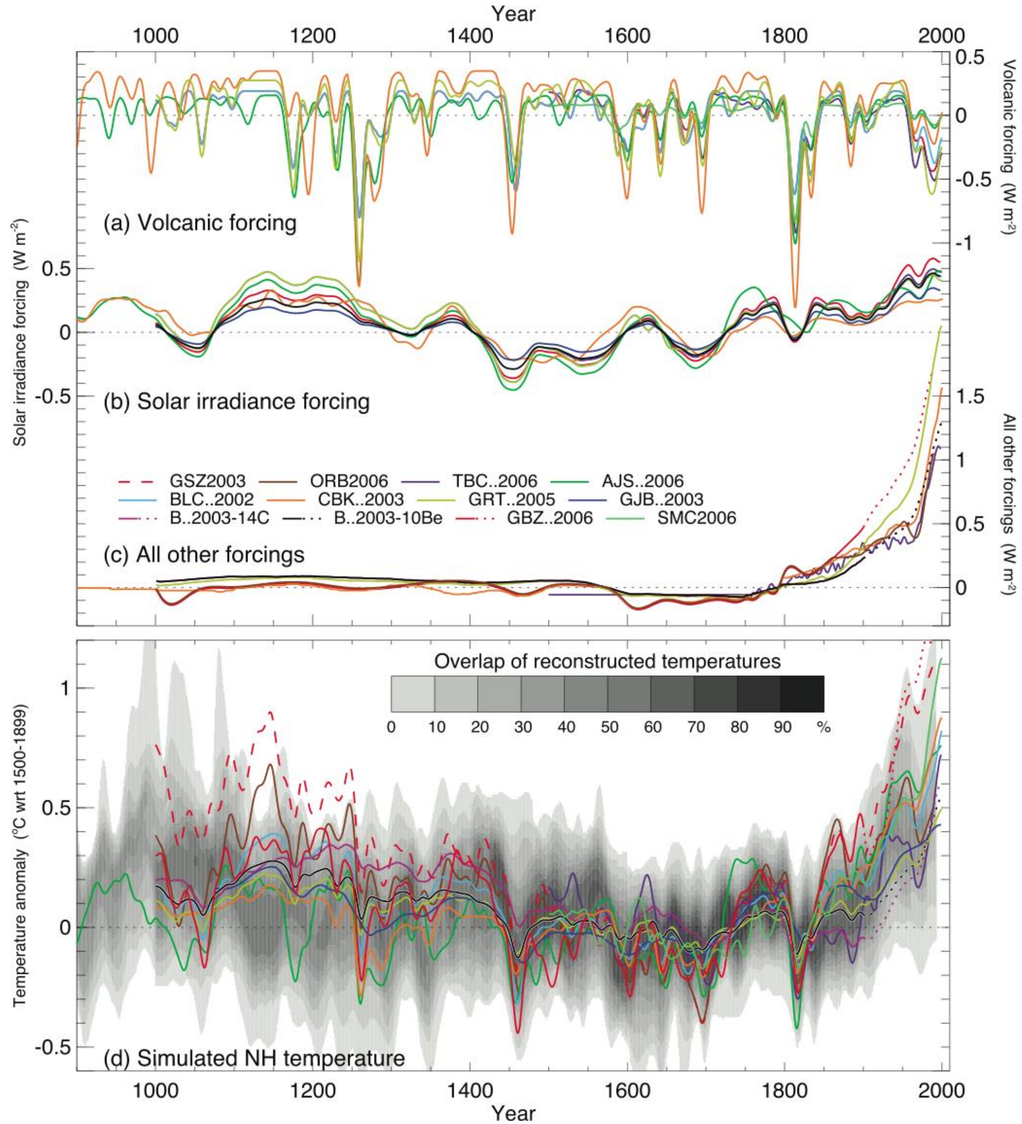
[a] Models: ECHO-G = ECHAM4 atmospheric GCM/HOPE-G ocean GCM, MAGICC = Model for the Assessment of Greenhouse-gas Induced Climate Change, HadCM3 = Hadley Centre Coupled Model 3; NCAR CSM = National Center for Atmospheric Research Climate System Model, MoBiDiC = Modèle Bidimensionnel du Climat , ECBilt-CLIO = ECBilt-Coupled Large-scale Ice Ocean, Bern CC = Bern Carbon Cycle-Climate Model, CLIMBER2 = Climate Biosphere Model 2, ECHAM4/OPYC3 = ECHAM4 atmospheric GCM/Ocean Isopycnal GCM 3.

[b] Forcings: S = solar, V = volcanic, O = orbital, G = well-mixed greenhouse gases, C = CO_2 but not other greenhouse gases, A = tropospheric sulphate aerosol, L = land use change, Z=tropospheric and/or stratospheric ozone changes and/or halocarbons.

[c] EBM = Energy Balance Model.

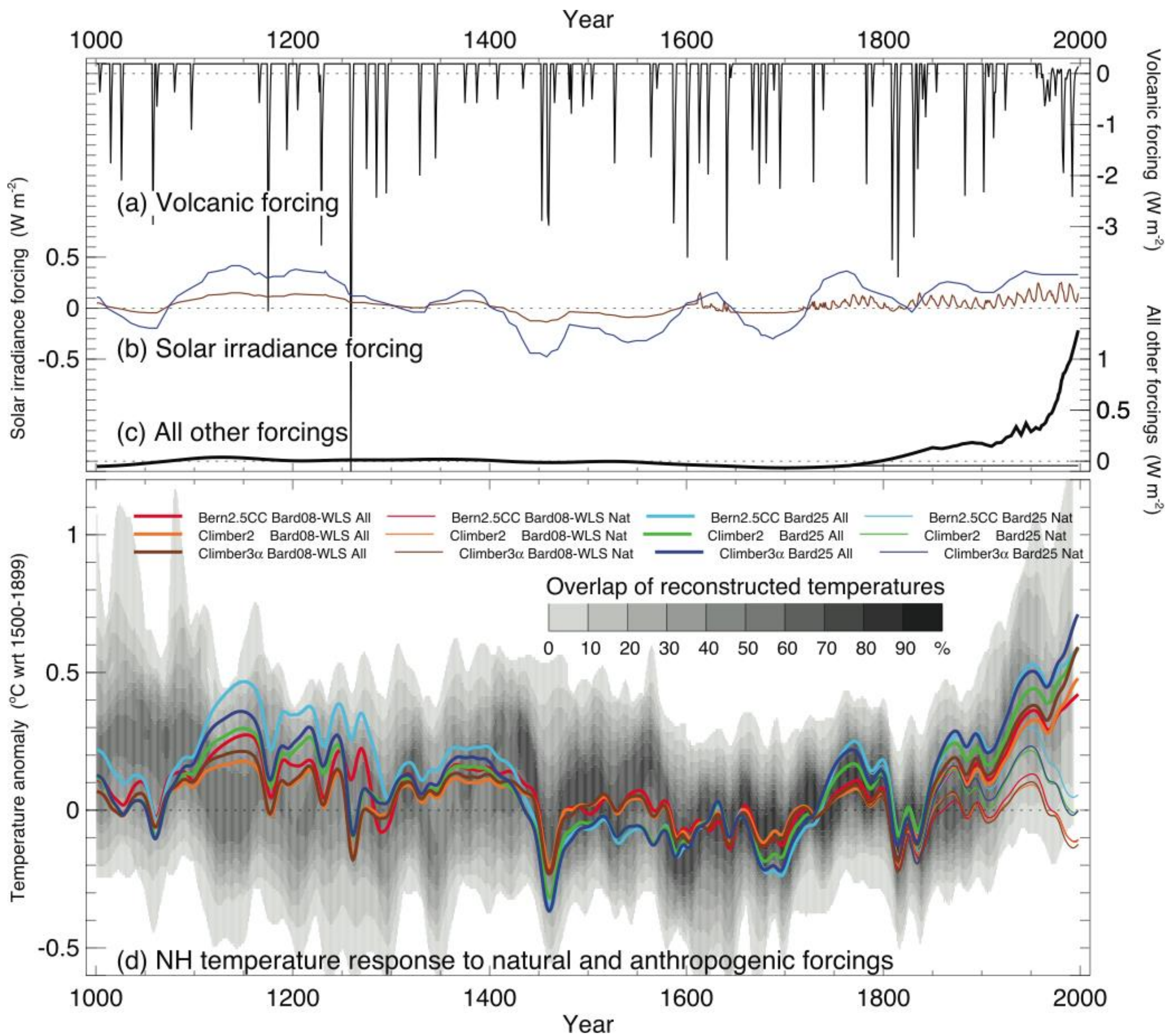
IPCC AR4 − Chapter 6 (2007)

IPCC AR4 LM radiative forcings − simulated NH temperature anomalies



IPCC AR4 − Chapter 6 (2007)

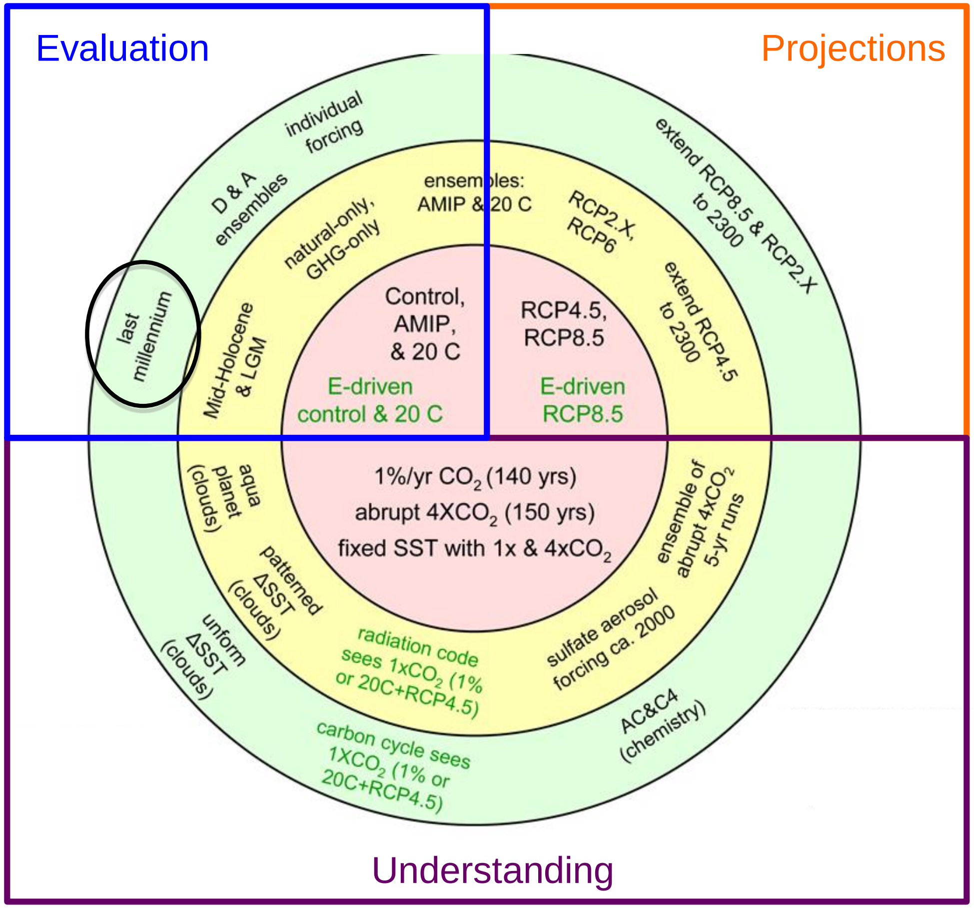
IPCC AR4 LM − sensitivity to weak or strong solar irradiance variations



IPCC AR4 − Chapter 6 (2007)

CMIP5 and PMIP3 —> IPCC AR5 (2013)

- New set of simulations that provide climate information and knowledge of particular relevance to future assessments of climate science



Last Millennium (850-1850) – officially CMIP5 and PMIP3

•Evaluate the ability of models to capture observed variability on multidecadal and longer time-scales.

•Determine fractions of the variability attributable to “external” forcing and purely internal variability.

•Provides a longer-term perspective for detection and attribution studies.

CMIP5: Same model – same resolution as projections; simulations available in CMIP5 database

PMIP3 in charge of experimental design

Taylor et al., BAMS (2012)

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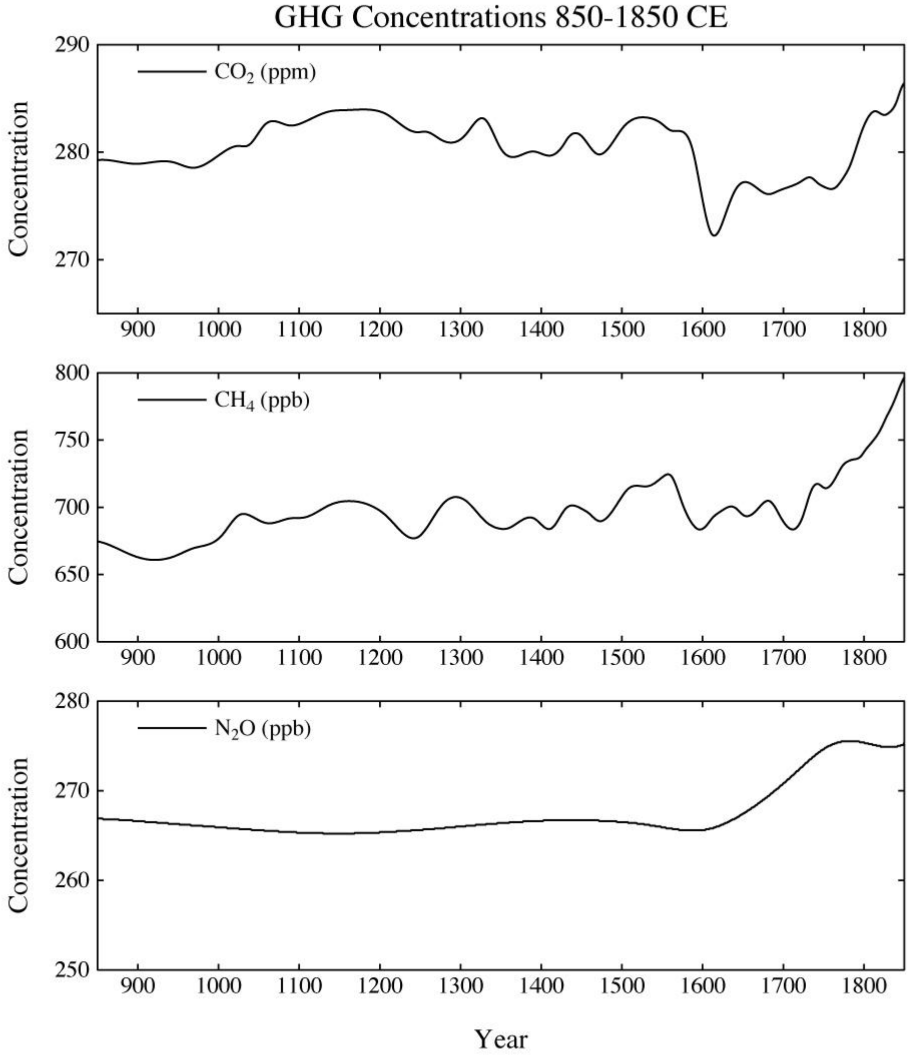
Last Millennium experimental design (850-1850AD)

Feature	PMIP3 recommendation	Alternate solution
Orbital parameters	Annually varying	
Date of vernal equinox	21 March at Noon	
Well-mixed greenhouse gases	Annually varying	
Volcanic aerosols	Two reconstructions (AOD, effective radius): GRA (Gao et al., 2008) CEA (Crowley et al., 2008)	
Solar irradiance	Multiple reconstructions (including spectral variations): WLS (back/noback)* (Wang et al., 2005) 1610–2005 VSK (Vieira et al., 2010) 850–1850 and merge to WLS (back) SBF (Steinhilber et al., 2009) 850–1850 and merge to WLS (back) MEA (back/noback) (Muscheler et al., 2007) 850–1610 and merge to WLS (back/noback) DB (back/noback) (Delaygue and Bard, 2010) 850–1610 and merge to WLS (back/noback)	
Ozone	Parameterisation of solar-related variations	Same as PI-control**
Tropospheric aerosols	Not prescribed	Same as PI-control
Vegetation	Land cover change (natural vegetation to crop/pasture)	Same as PI-control
Ice sheets	No changes from PI-control	
Topography and coastlines	Same as in PI-control	

Schmidt et al., GMD (2011)

Greenhouse gas forcing − CO_2, CH_4, and N_2O

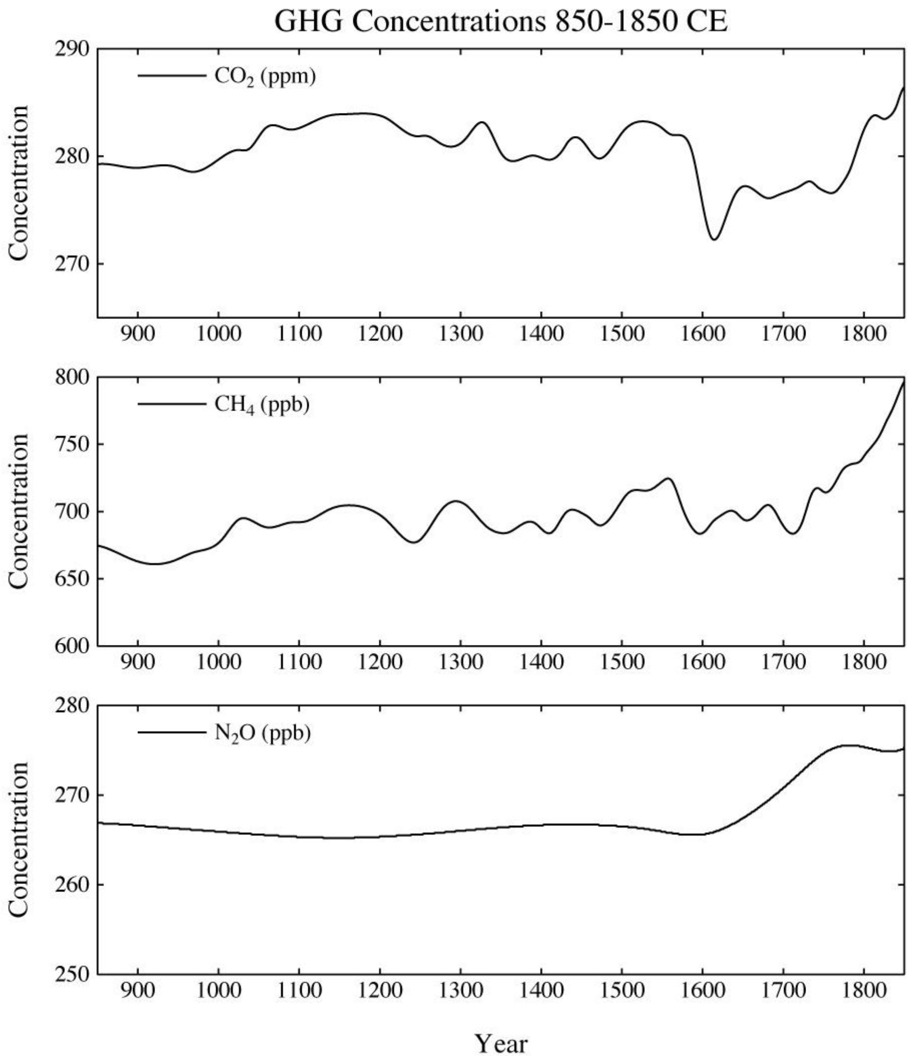


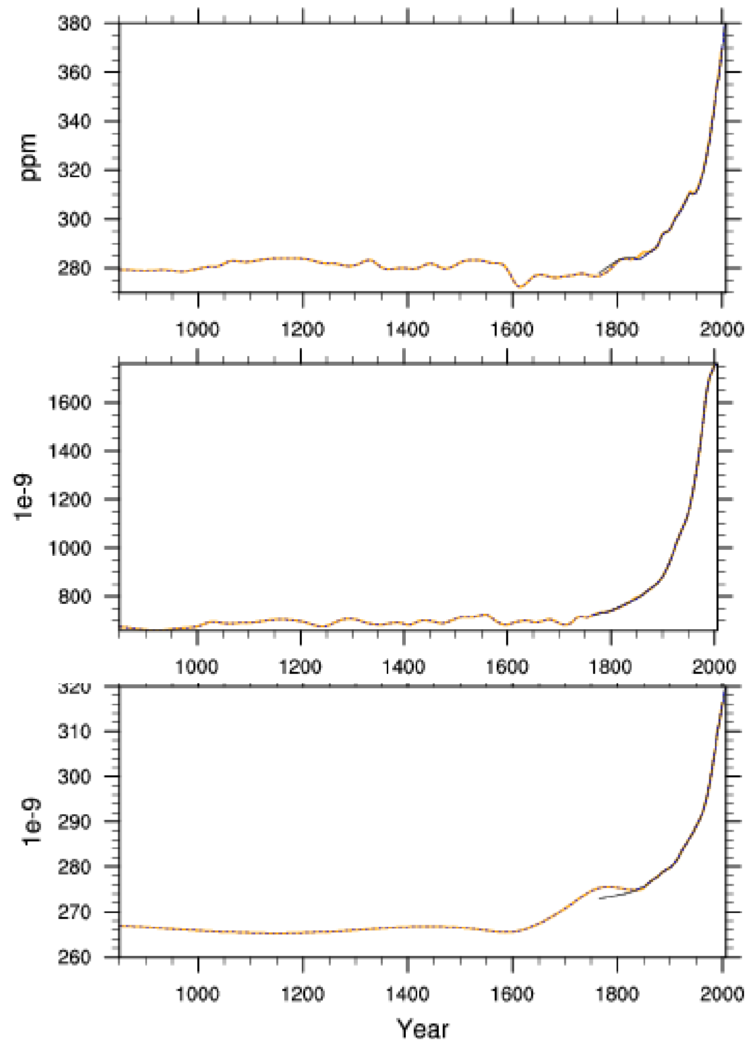
CO_2, CH_2, N_2O evolution

- CO_2 and CH_4: Law Dome Ice data.
- N_2O: spline fit through various ice cores (DomeC, GRIP, EUROCORE, H15)
- Industrial period trace gases are linked with splines with ice core data

Schmidt et al., GMD (2011)

Greenhouse gas forcing − into historical period

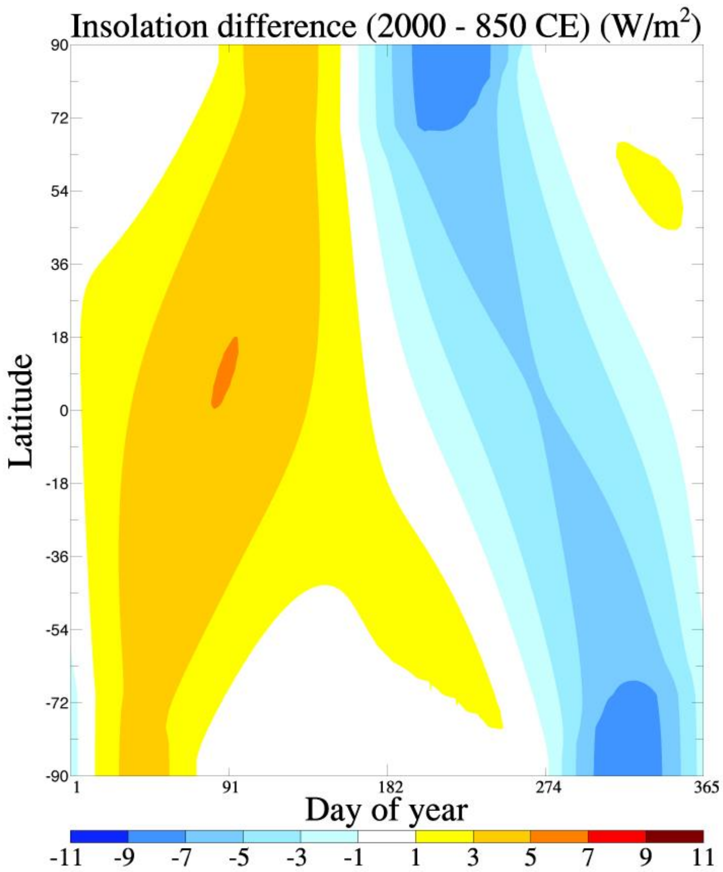


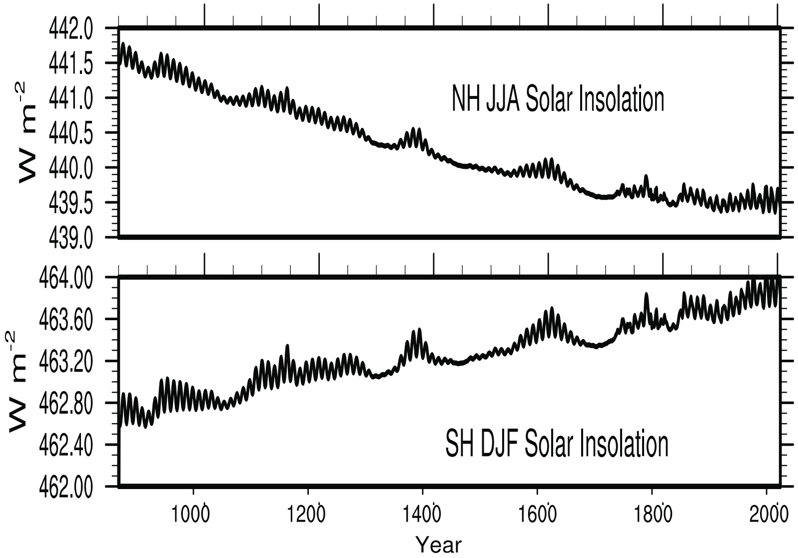


Landrum et al., JClimate (2013)

Orbital forcing – two options

- Calculated in model using Berger
- Specified from table on web site

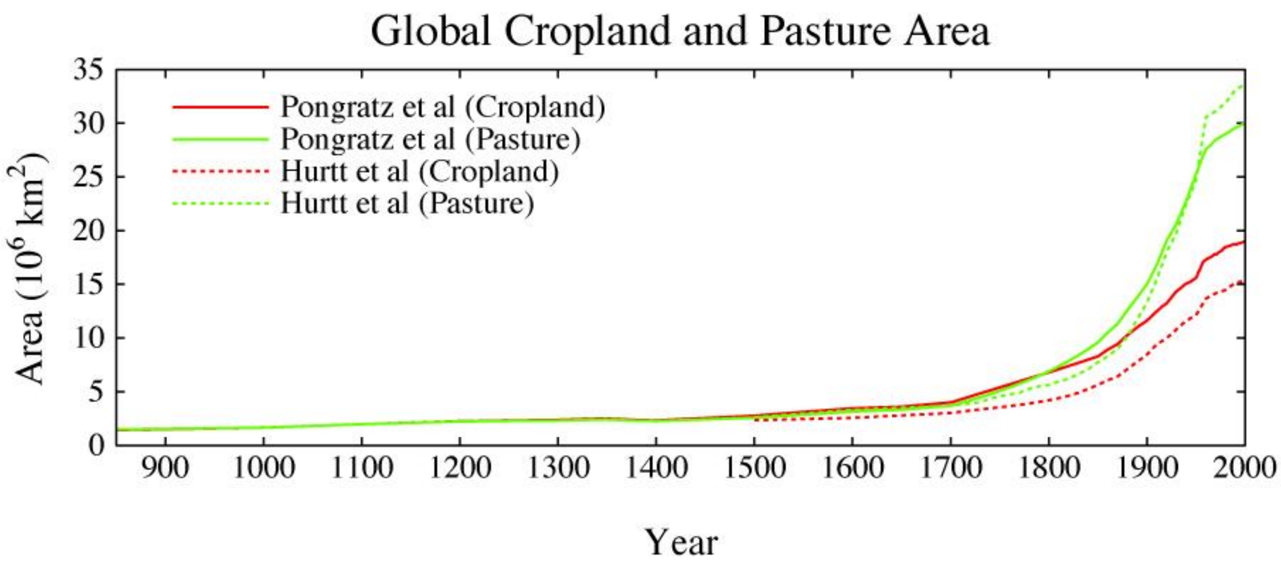


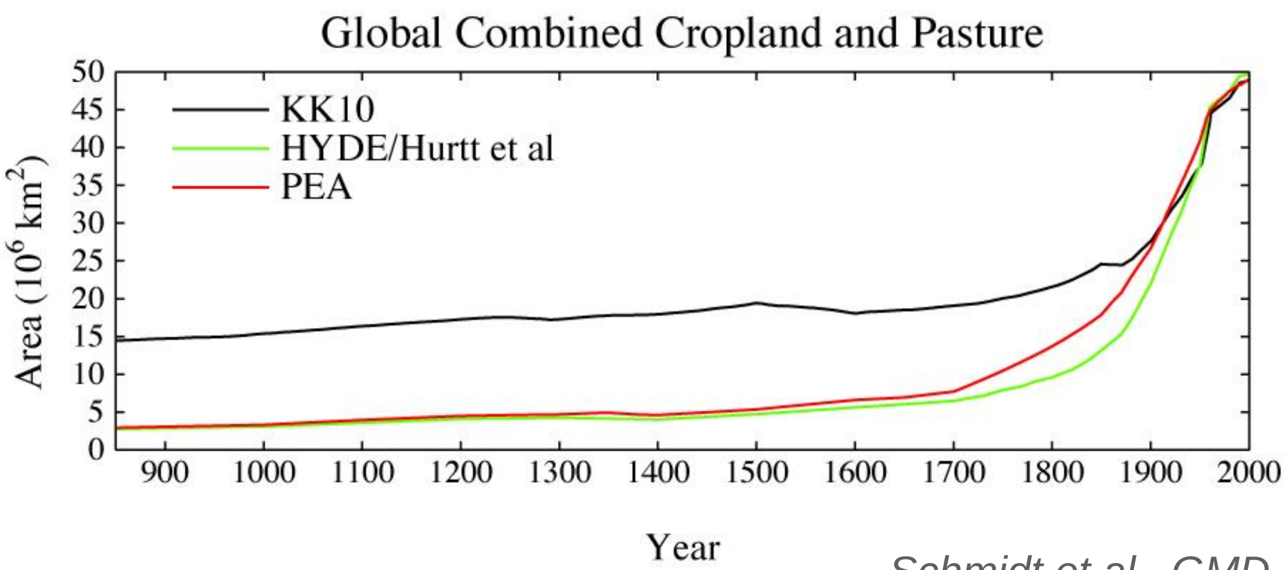


Schmidt et al., GMD (2011)

Landrum et al., JClimate (2013)

Land use boundary conditions

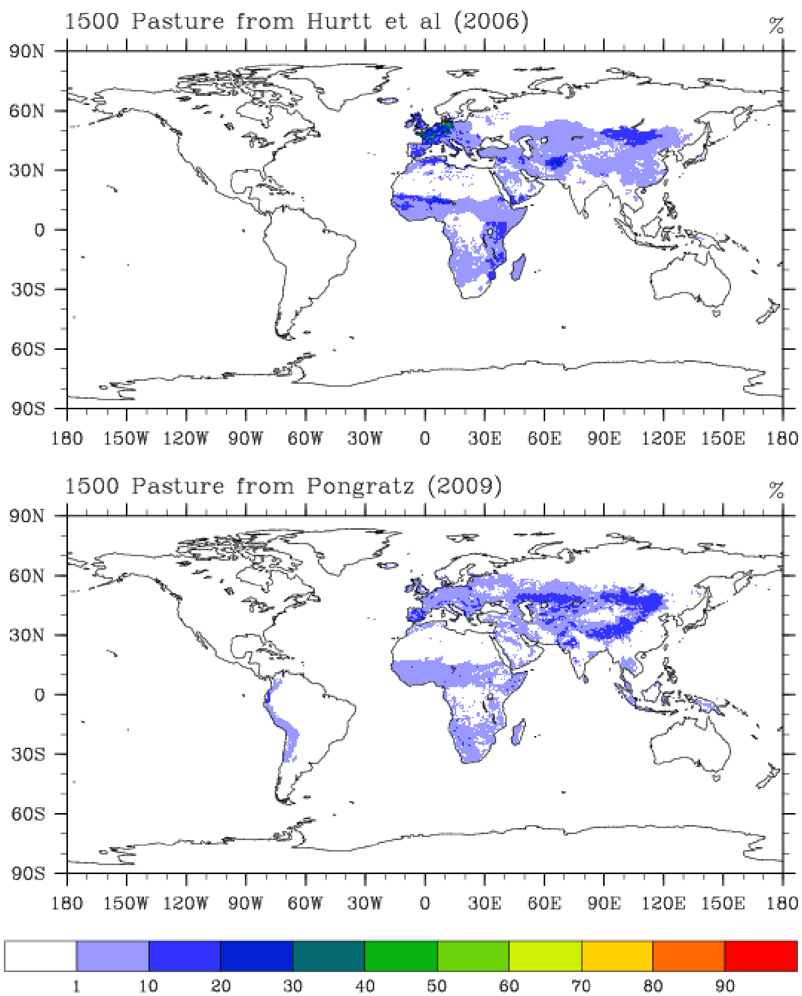




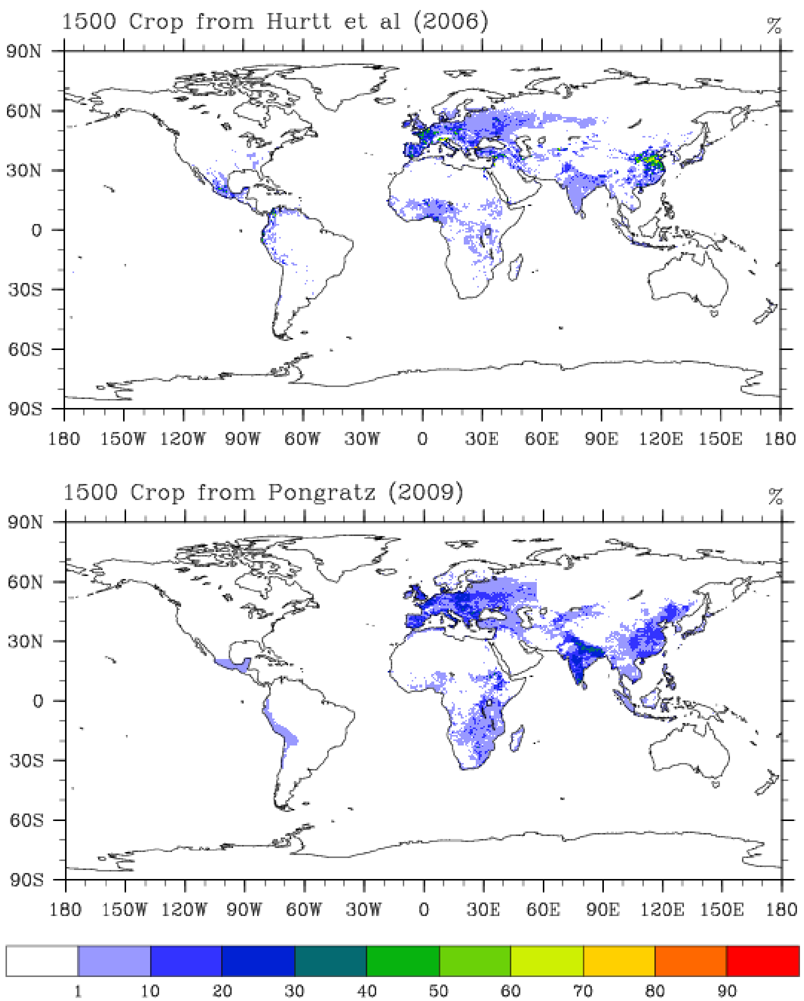
Schmidt et al., GMD (2011, 2013)

Pasture and Crops at 1500 from Hurtt vs Pongratz

Pasture

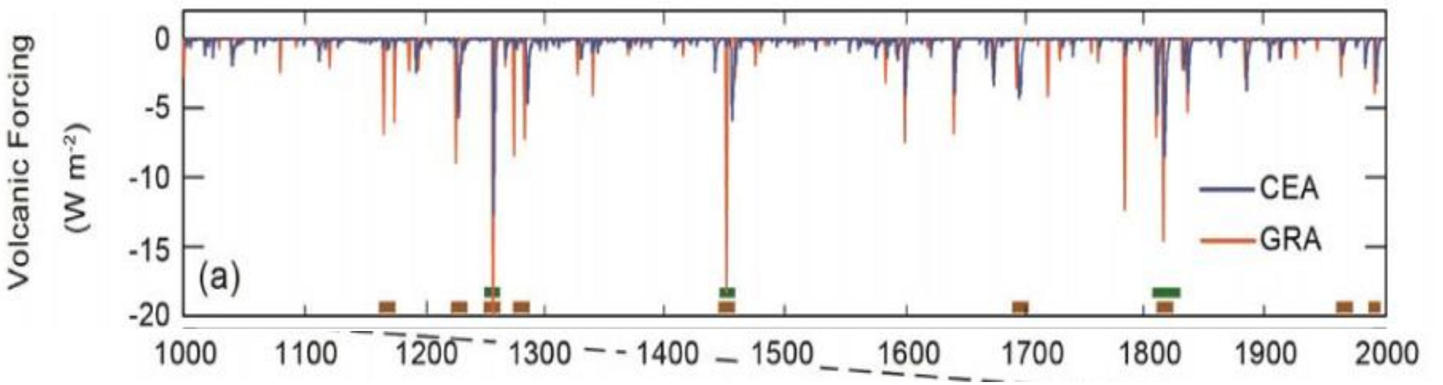


Crop

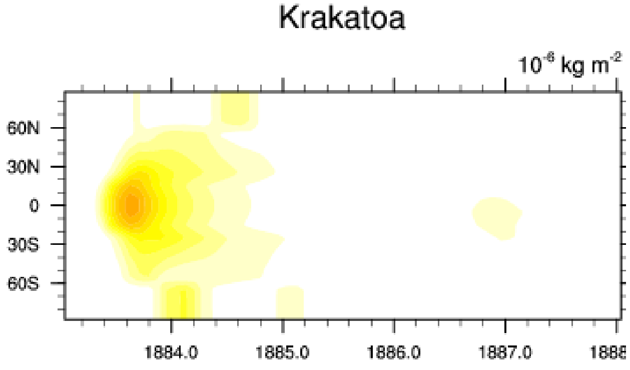


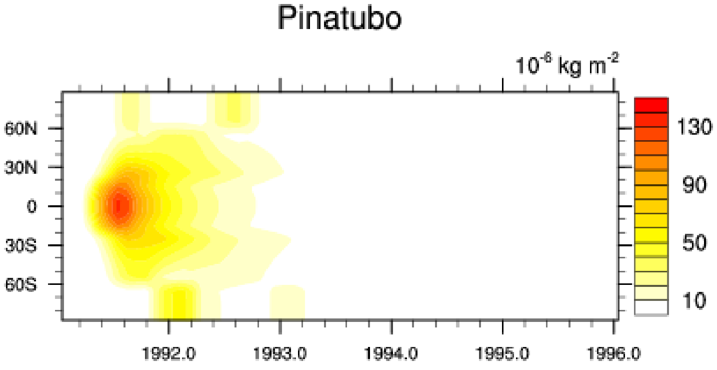
Volcanic forcing – two options – many implementations

- Crowley & Unterman (CEA) and Gao-Robock-Ammann(GRA) based on multiple ice cores: Antarctic and Greenland



- Combined with atmospheric modeling of aerosol distribution and optical depth

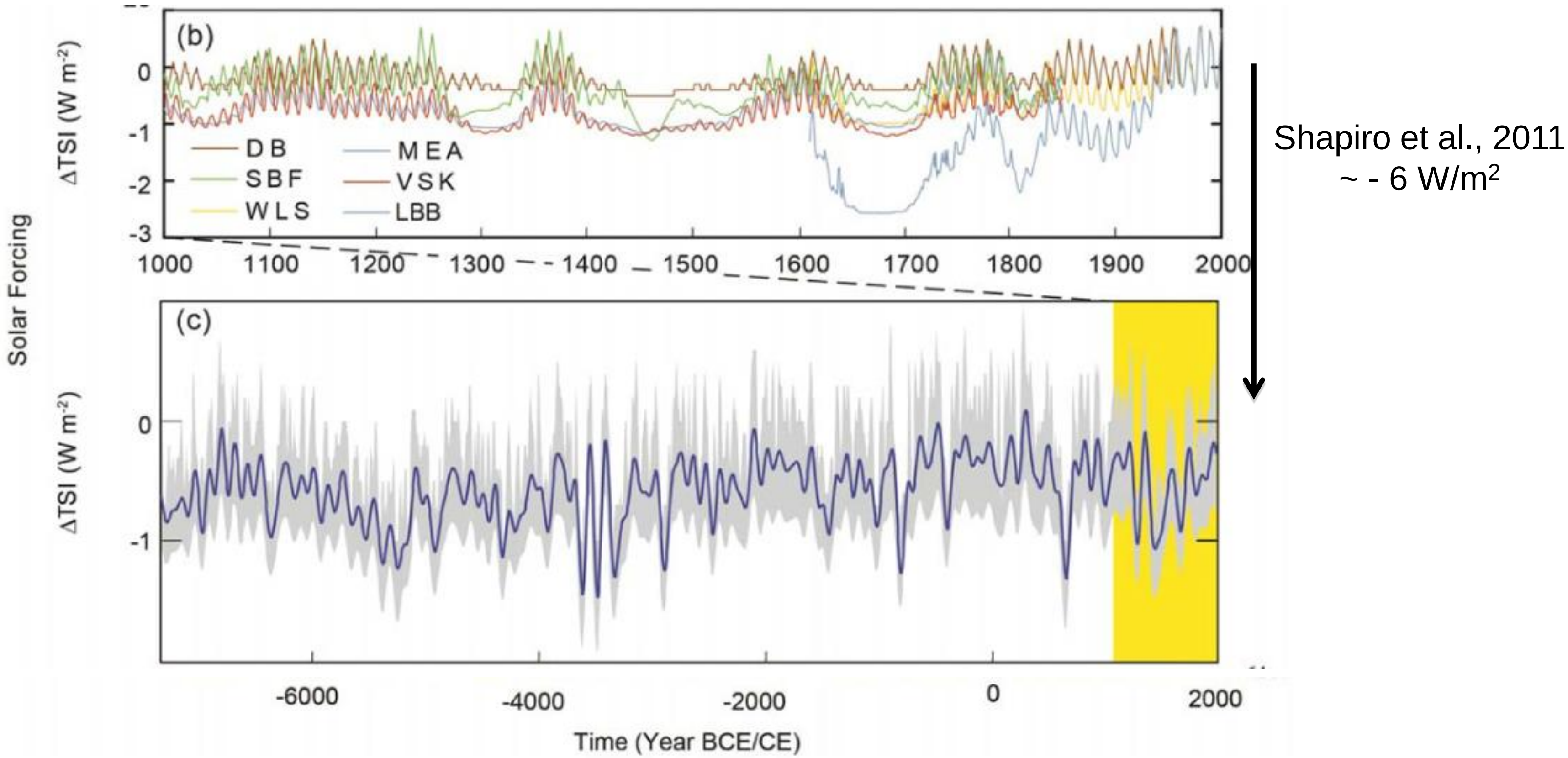




IPCC AR5 – Chapter 5 (2013)

Solar irradiance variations − many options

- ΔTSI at Maunder Minimum: 0.04 to 0.1% (RF -0.1 to -0.23 W m^{-2})
- 11-year solar cycle (synthetic before 1610 AD)
- Scaling of spectral variations to TSI
- Solar-related ozone changes



IPCC AR5 – Chapter 5 (2013)

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PMIP3 – CMIP5 Last Millennium simulations

PMIP3 / CMIP5 past1000 Boundary Conditions
Information as of April 5th 2013

Up to date info: https://pmip3.lsce.ipsl.fr/wiki/doku.php/pmip3:database:status
Official past1000 BC on PMIP3 wiki https://wiki.lsce.ipsl.fr/pmip3/doku.php/pmip3:design:lm:final
past1000 GMD paper http://www.geosci-model-dev.net/5/185/2012/

	Institute	Country	LM *past1000* *(1000 years)*	CMIP5	Carbon cycle	Atm	Ocn	Model id	Ensemble	Orbital parameters	Vernal equinox	GHG	Volcanic aerosols	Solar irradiance	Ozone	Tropos aerosols	Land Use Land Cover	Ice sheet	Topo
1	BCC	China	CMIP5	Yes	Yes	128×64 x L26	360x232 x L40	bcc-csm1-1	r1i1p1	PMIP3 precomputed table	March 21 at Noon	Joos table	GRA	VSK + WLS back	Same as piControl before 1850, as historical afterward		Same as piControl		
2	BCCR	Norway	Running Summer 2013	No	Yes	96×48 x L26	100×116 x L32	NorESM1-L	Running… Summer 2013										
3	NASA-GISS	USA	CMIP5	Yes	No	144x90 x L40	288x180 x L32	GISS-E2-R	r1i1p121	Internally calculated (Berger 1978)	March 21 at Noon	Joos table	CEA	SBF	Same as piControl before 1850, as historical afterward		PEA	Same as piControl	
									r1i1p122				GRA (4)						
									r1i1p123				None						
									r1i1p124				CEA	VSK + WLS back					
									r1i1p125				GRA (4)				KK10		
									r1i1p126				None				PEA		
									r1i1p127				CEA				KK10		
									r1i1p128				GRA (4)				PEA		
4	IPSL	France	CMIP5	Yes	Yes	96x95 x L39	182x149 x L31	IPSL-CM5A-LR	r1i1p1	Internally calculated (Berger 1978)	March 21 at Noon	Joos table	GRA	VSK + WLS back	Same as piControl				
5	LASG - IAP	China	CMIP5	Yes	No	128x108 x L26	360x180 x L30	FGOALS-s2	r1i1p1	PMIP3 precomputed table	March 21 at Noon	Joos table	GRA	VSK + WLS back	Same as piControl before 1850, as historical afterward		Same as piControl		
6			CMIP5	Yes	No	72x45 x L26	360x180 x L30	FGOALS-gl	r1i1p1	Internally calculated (Berger 1978)	March 21 at Noon	Ammann et al (2007)	Crowley (2000)	Crowley (2000)	Same as piControl before 1850, as historical afterward		Same as piControl		
7	LOVECLIM	Belgium France Netherlands	Completed	No	No	32x64 x L3	122x65 x L20	LOVECLIM1-2		Internally calculated (Berger 1978)	March 21 at Noon	Joos table	CEA	DB		(1)	PEA	Same as piControl	
8	MIROC	Japan	CMIP5	Yes	Yes	128x64 x L80	256x192 x L44	MIROC-ESM	r1i1p1	PMIP3 precomputed table	March 21 at Noon	CO2: model predicting CH4&N2O:Joos table	CEA	DB + WLS	Same as piControl				
9	MPI-M	Germany	CMIP5	Yes	No	196x98 x L47	256x220 x L40	MPI-ESM-P	r1i1p1	PMIP3 precomputed table	March 21 at Noon	Joos table	CEA	VSK + WLS back	Regression (3)	Same as piControl	PEA	Same as piControl	
10	MRI	Japan	Running September 2013	Yes	No	320x160 x L48	364x368 x L51	MRI-CGCM3	Running… September 2013	Internally calculated (Berger 1978)	March 21 at Noon	Joos table	GRA	DB back + WLS back	Shindell et al	(2)	Same as piControl	Same as piControl	
11	NCAR	USA	CMIP5	Yes	No	288x192 x L26	320x384 x L60	CCSM4	r1i1p1	Internally calculated (Berger 1978)	March 21 at Noon	Joos table	GRA	VSK	Same as piControl	Same as piControl	PEA	Same as piControl	
12	MOHC (UK groups)	UK	Running Spring 2013	Yes	Yes	192x144 x L38	360x216 x L40	HadGEM2-ES	Running Spring 2013	Internally calculated (Berger 1978)	March 21 at Noon	Joos table	CEA	SBF + WLS Back	Same as piControl		PEA	Same as piControl	
13	UOED		PMIP3	No	No	96×73 x L19	288x144 x L20	HadCM3	r1i1p1	Internally calculated (Berger 1978)	March 21 at Noon	Joos table	CEA	SBF + WLS Back	Same as piControl		PEA	Same as piControl	
14	UNSW	Australia	PMIP3	No	No	64x56 x L18	128x112 x L21	CSIRO-Mk3L-1-2	r1i1p1	Internally calculated (Berger 1978)	March 21 at Noon	Joos table	CEA	SBF	Same as piControl				
15	UofT	Canada	Completed	No	No	256x128 x L26	320x386 x L40	UofT-CCSM3		Internally calculated (Berger 1978)	March 21 at Noon	Joos table	CEA	VSK + WLS back	Same as piControl				

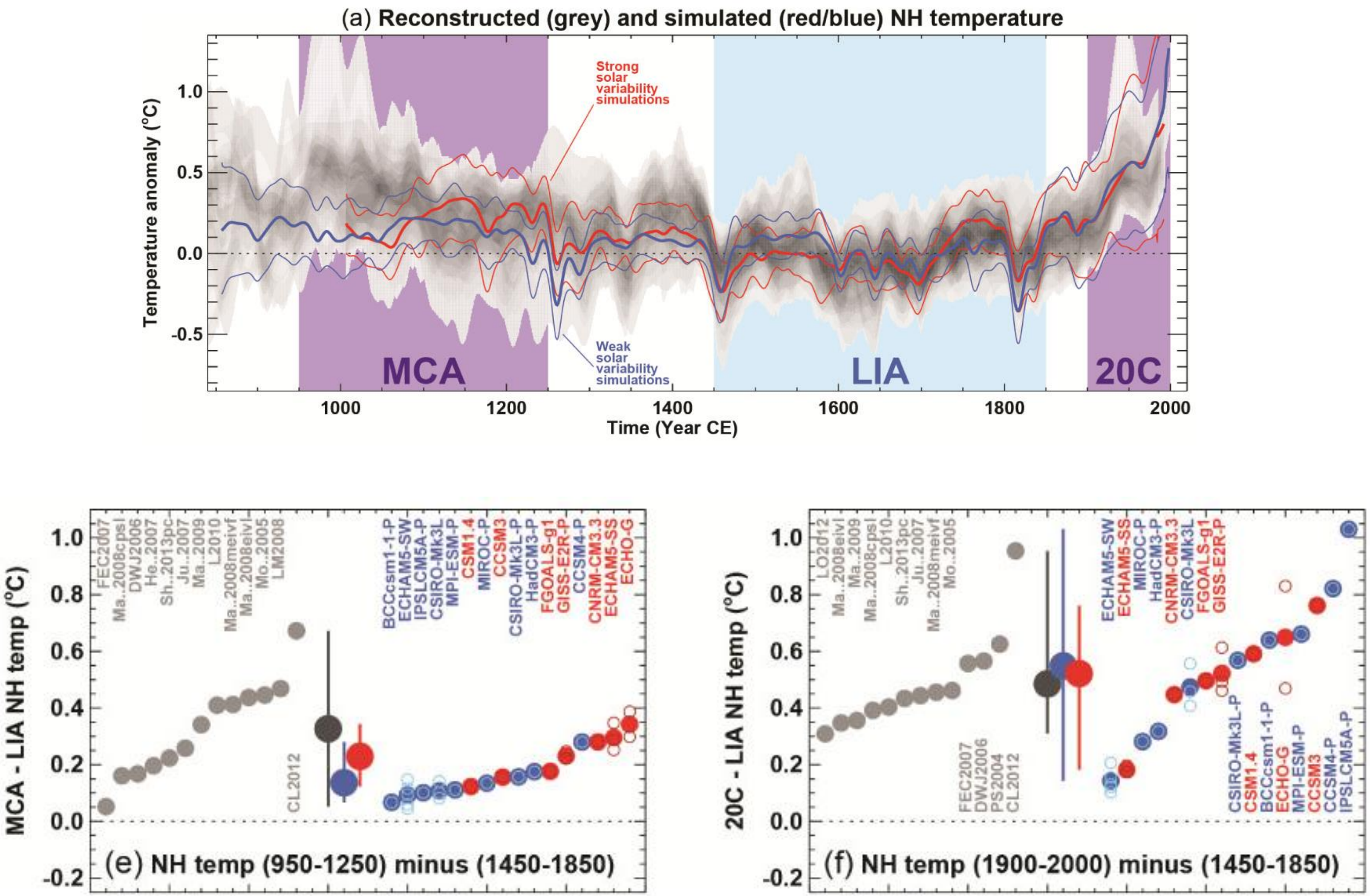
Click for up-to-date exp check : past1000 ?

Legend

Status expected completion date	Available in CMIP5 DB
No / Yes	Available in PMIP3 DB

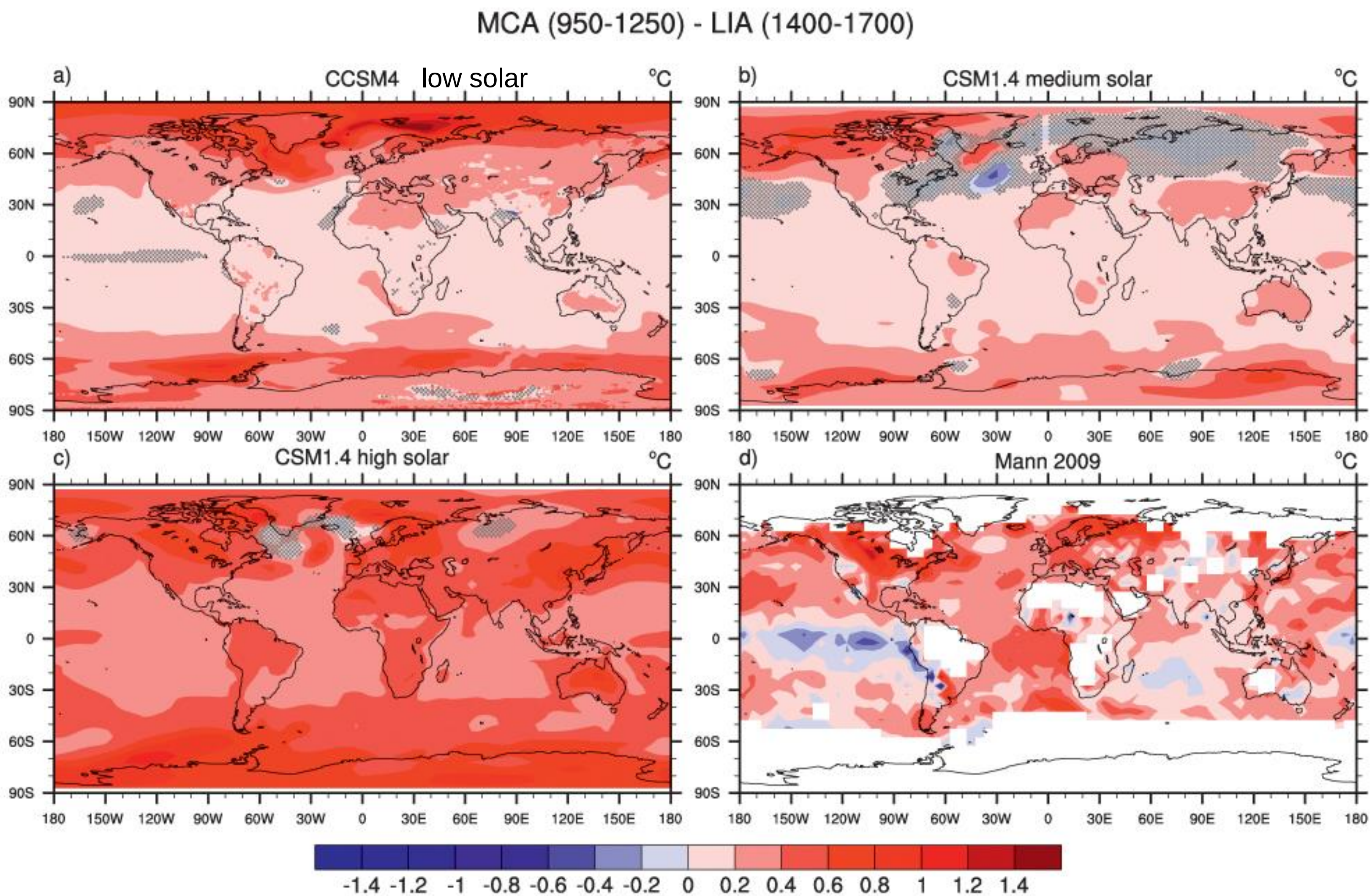
(1) LOVECLIM1-2 Changes in sulfate aerosol load are taken into account through modifications in the surface albedo (Charlson et al., 1991)
(2) MRI-CGCM3 RCP scenario in 1765 other than biomass burning. Biomass burning in 1850
(3) MPI-ESM-P In the case of ozone we construct the data using monthly data from the ACC/SPARC climatology recommended for CMIP5 averaged over the years 1850-1860, and add solar dependence by using regression coefficients calculated from the full ACC/SPARC climatology together with 180.5nm solar flux from the VSK data. For details, see see H. Schmidt et al., The response of the middle atmosphere to anthropogenic and natural forcing in MPI-ESM, accepted for publication, Journal of Advances in Modeling Earth Systems
(4) GISS-E2-R Due to a conversion factor error in the specification, the forcing is twice as large as it should be

IPCC AR5 LM: Simulated NH temperatures



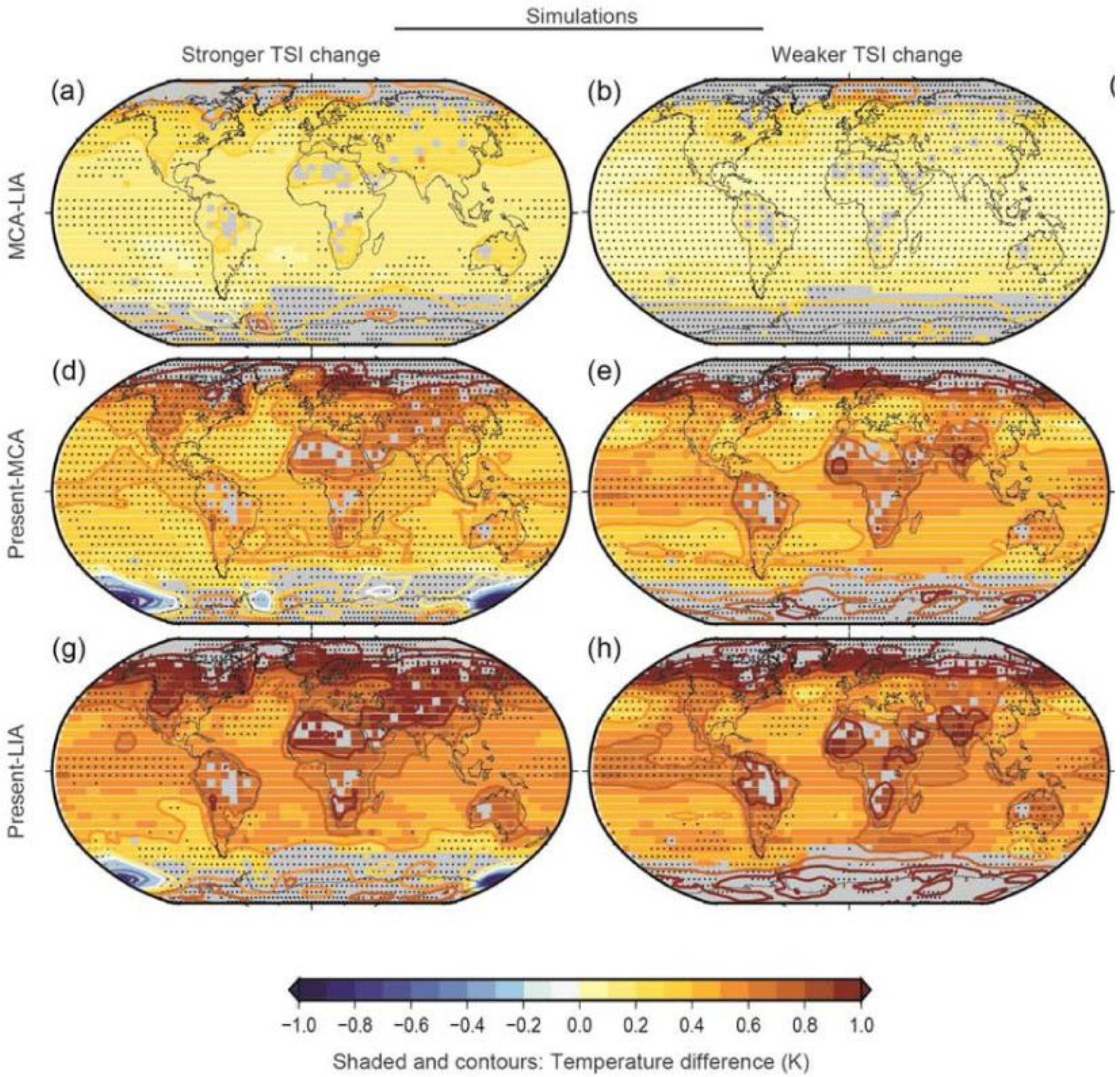
IPCC AR5 – Chapter 5 (2013)

Response = f(forcing, implementation, climate "sensitivity", internal variability)



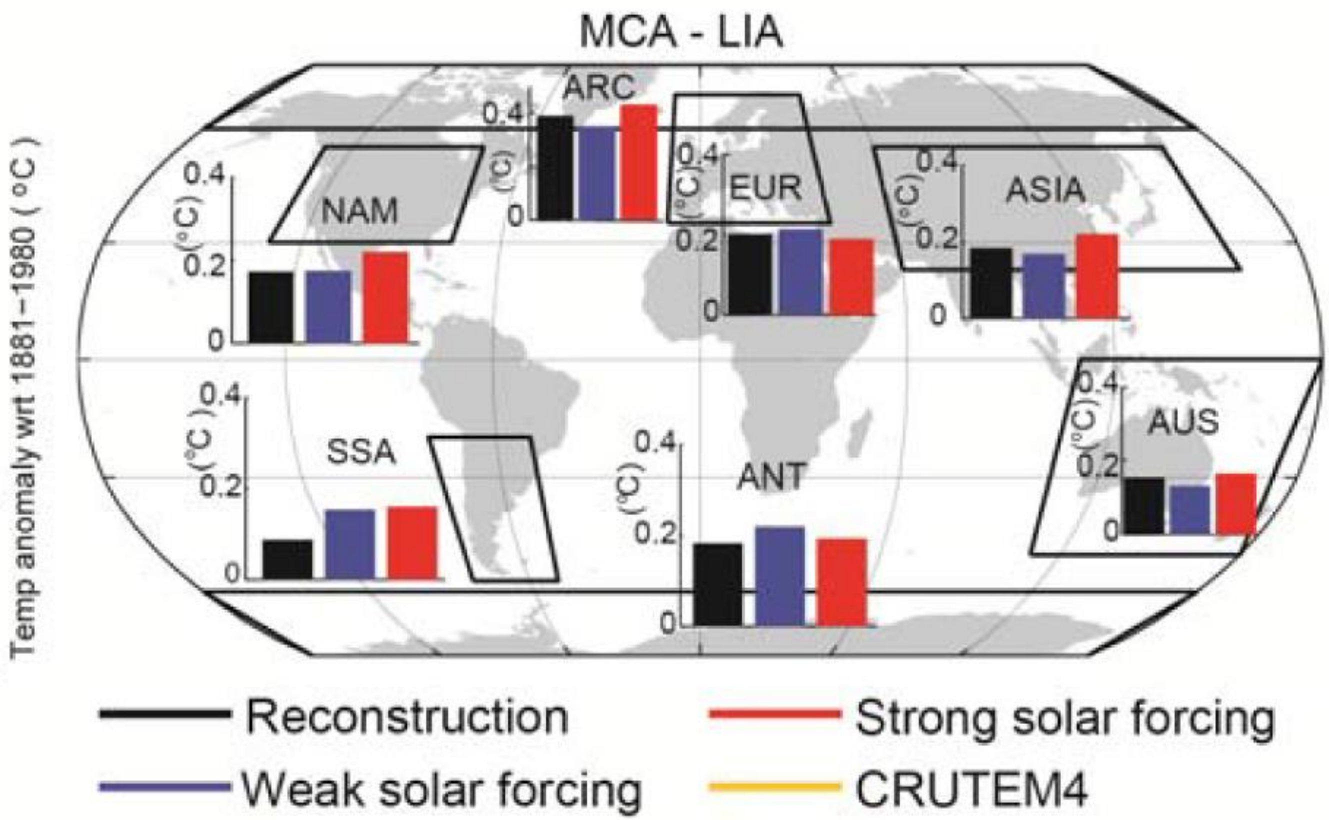
Landrum et al., JClimate (2013)

IPCC AR5 LM − sensitivity to weak or strong solar irradiance variations



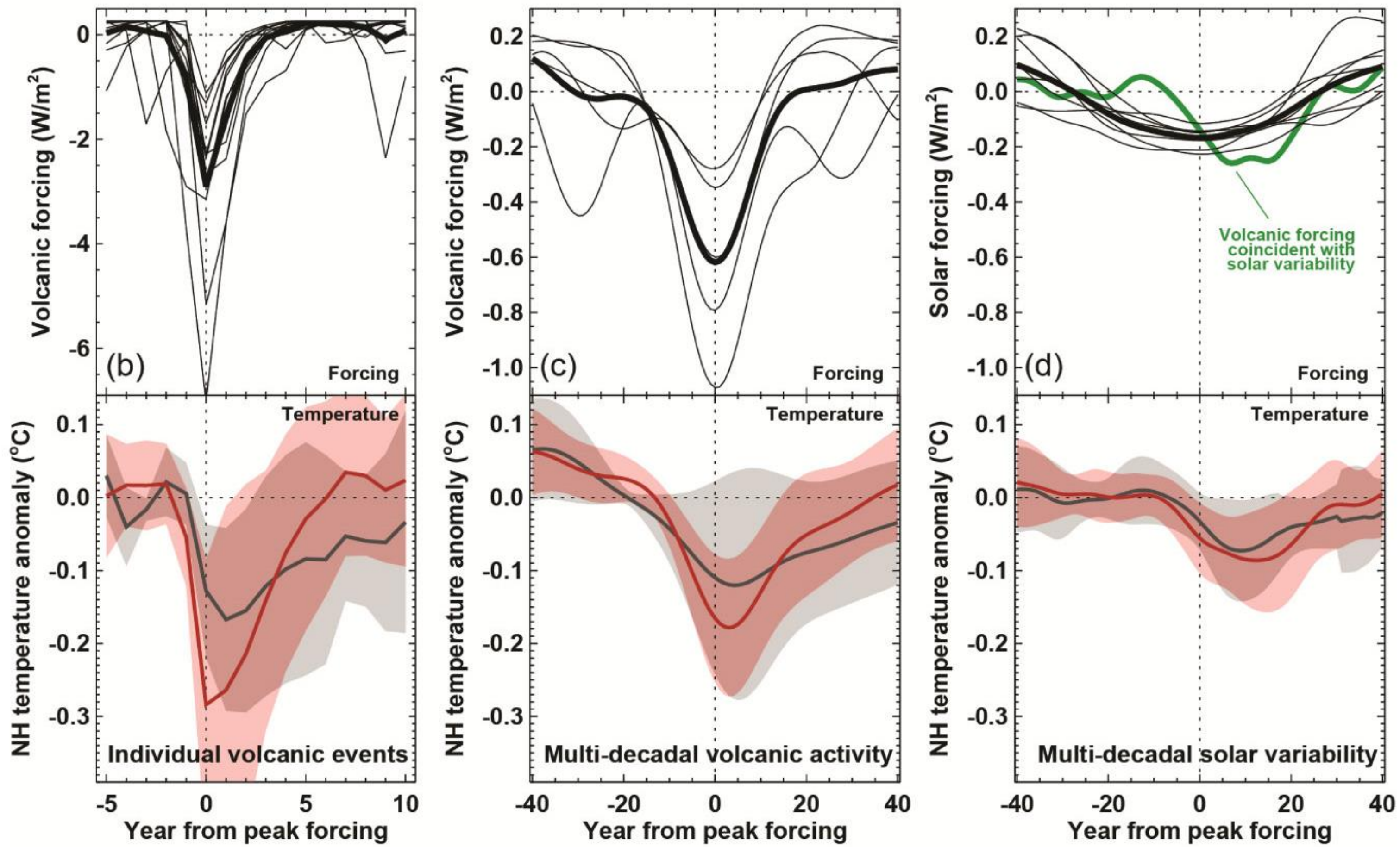
IPCC AR5 – Chapter 5 (2013)

IPCC AR5 LM − sensitivity to weak or strong solar irradiance variations



IPCC AR5 – Chapter 5 (2013)

IPCC AR5 LM − Spread of responses to volcanic and solar forcing

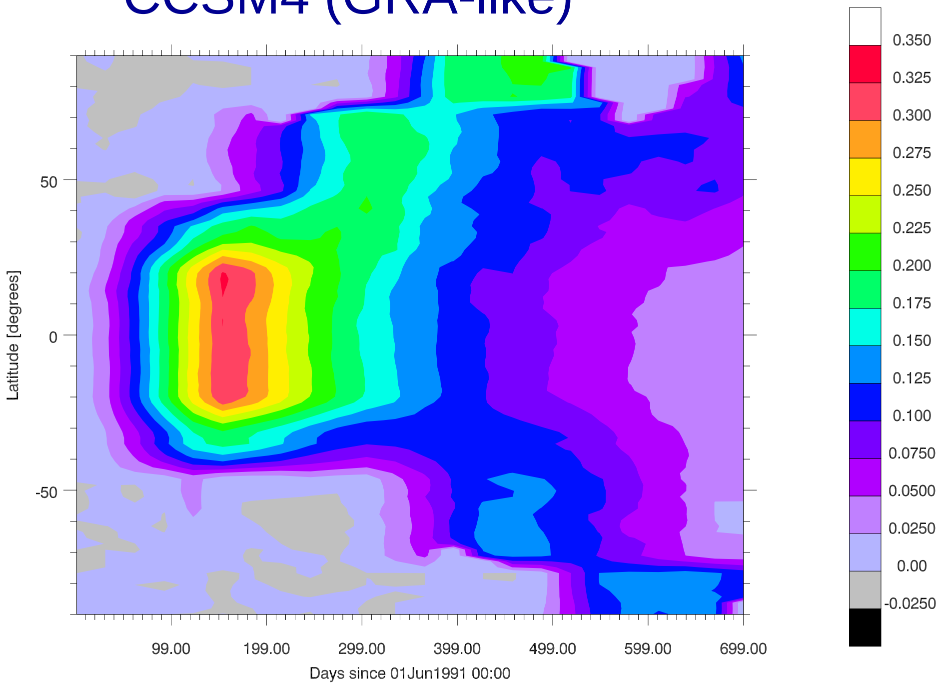


IPCC AR5 – Chapter 5 (2013)

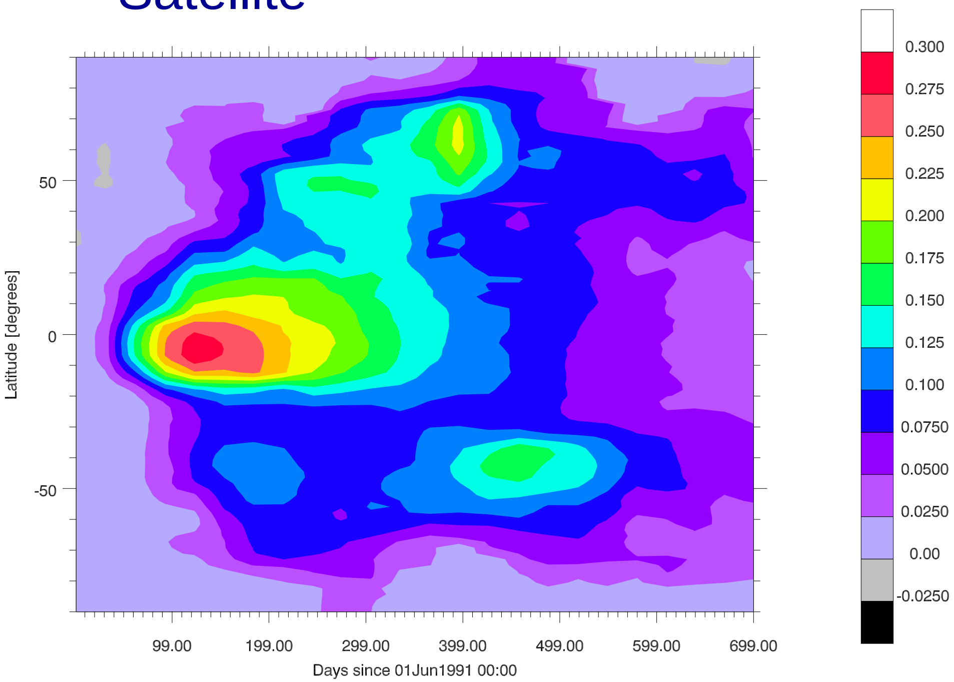
Response = f(forcing, implementation, climate sensitivity, internal variability)

- Forcing: CEA, GRA … satellite measurements

CCSM4 (GRA-like)



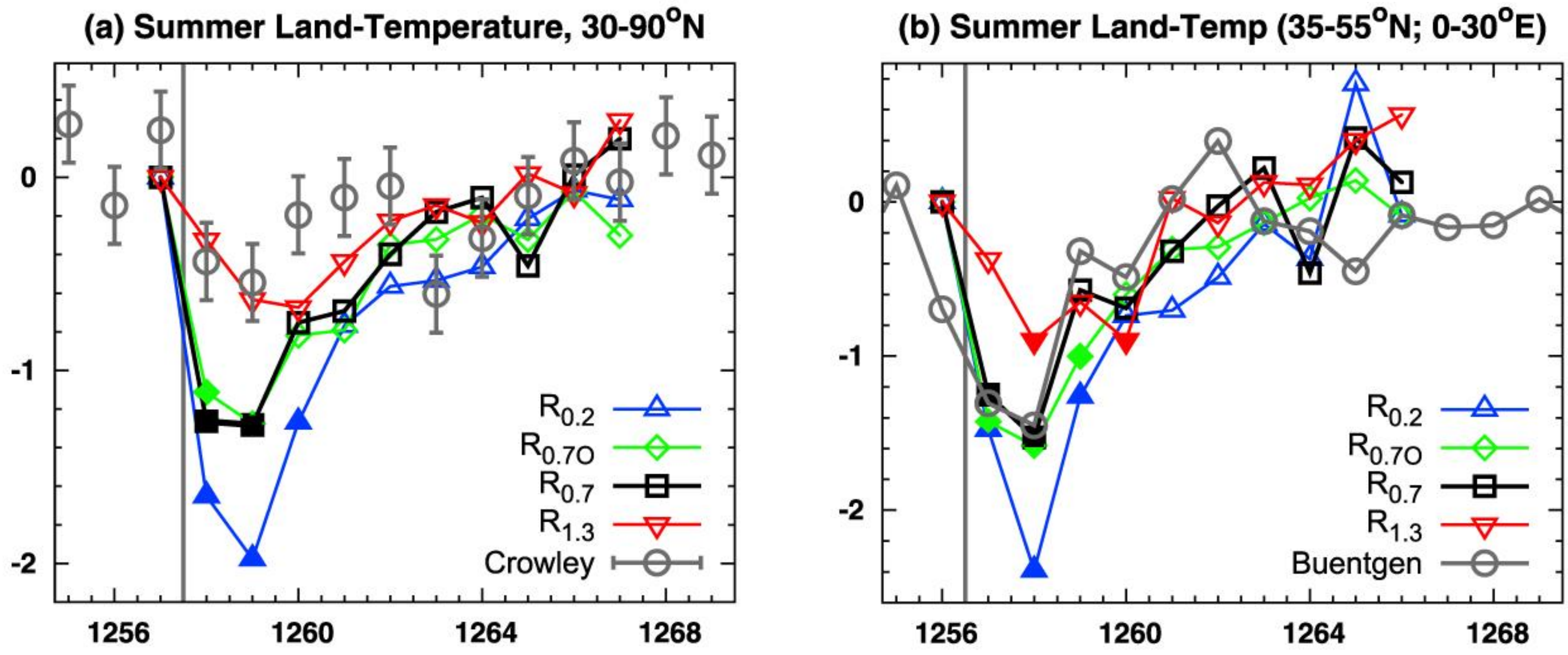
Satellite



Courtesy of A. Conley et al.

Response = f(forcing, implementation, climate sensitivity, internal variability)

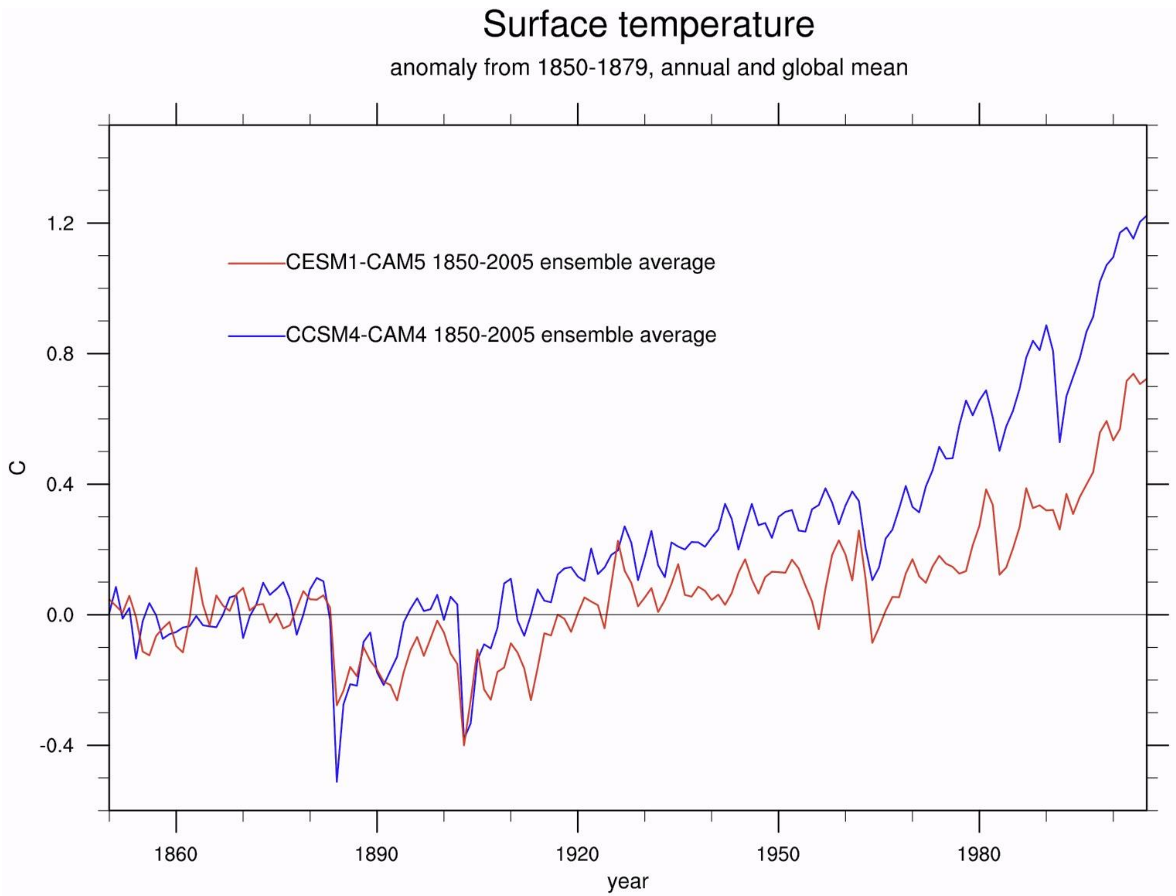
- Implementation: alter TSI, single size aerosols in layers above tropopause, multiple size distributions



Timmreck et al., GRL (2009)

Response = f(forcing, implementation, climate "sensitivity", internal variability)

- Climate "sensitivity"



1258 eruption

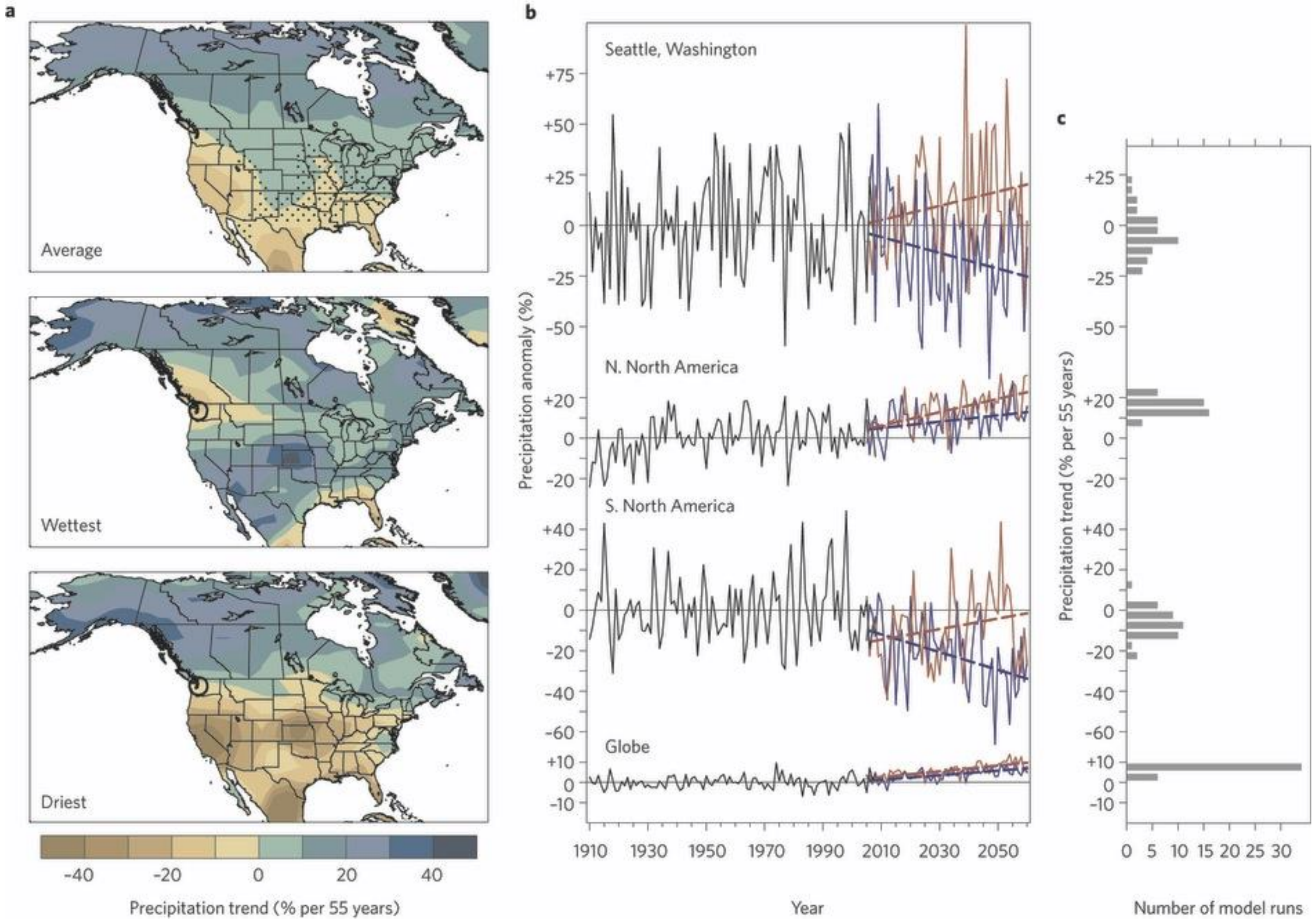
CCSM4-CAM4: 2.7° C

CESM1-CAM5: 1.4° C

Courtesy of G. Strand

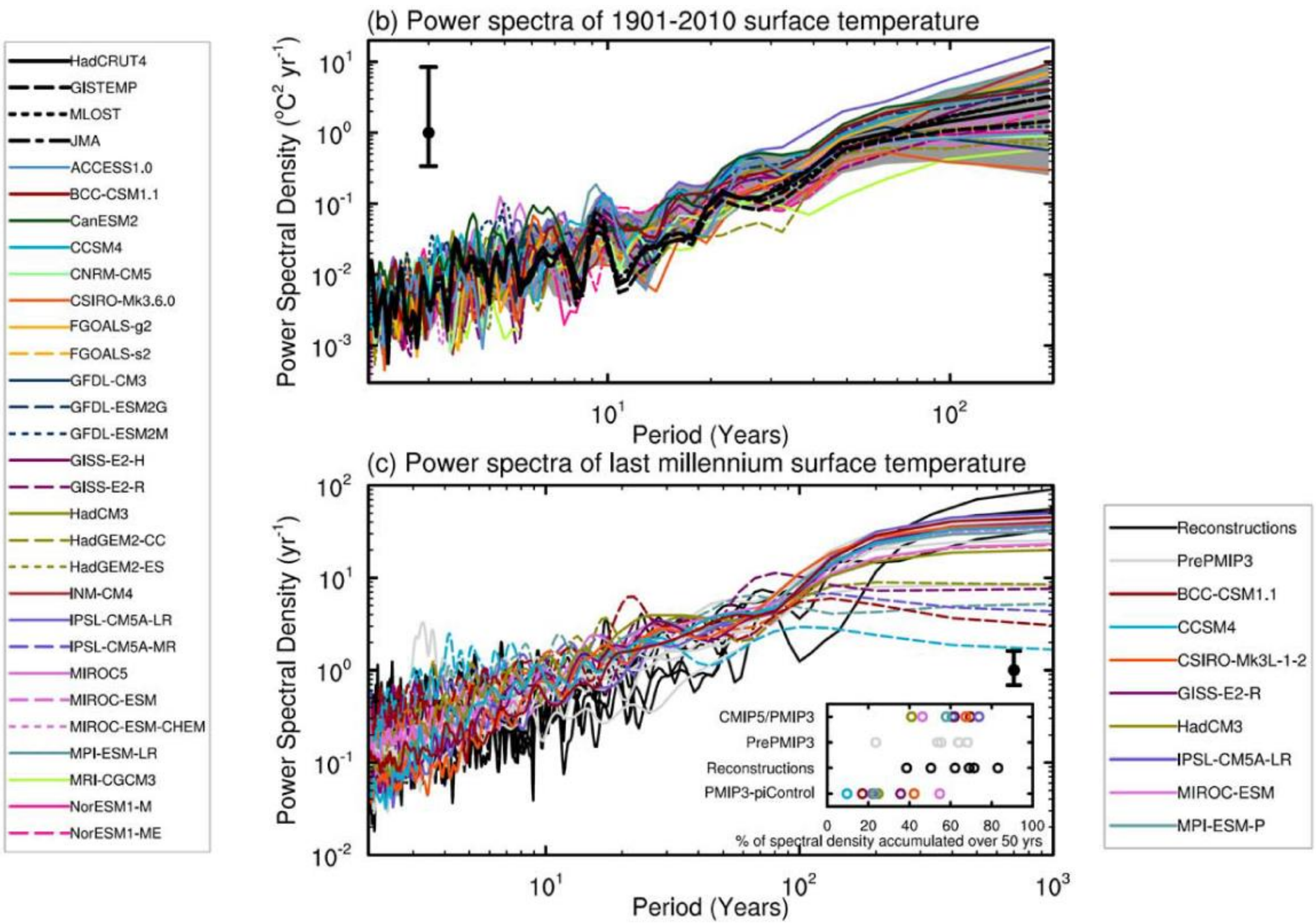
Response = f(forcing, implementation, climate "sensitivity", internal variability)

- Internal variability



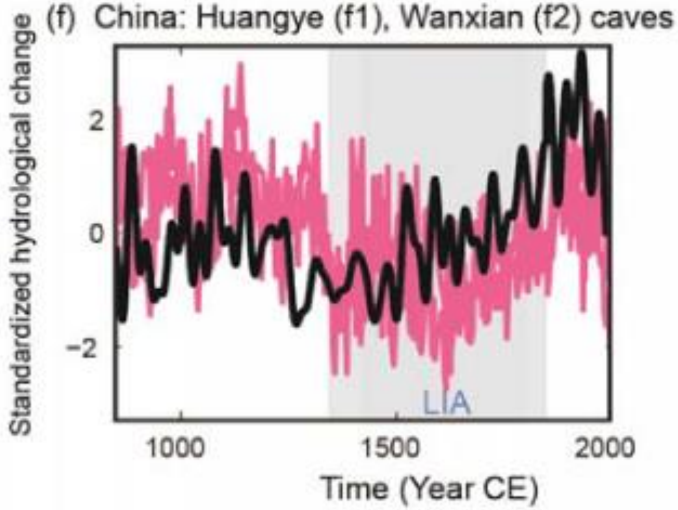
Deser et al., NCC (2012)

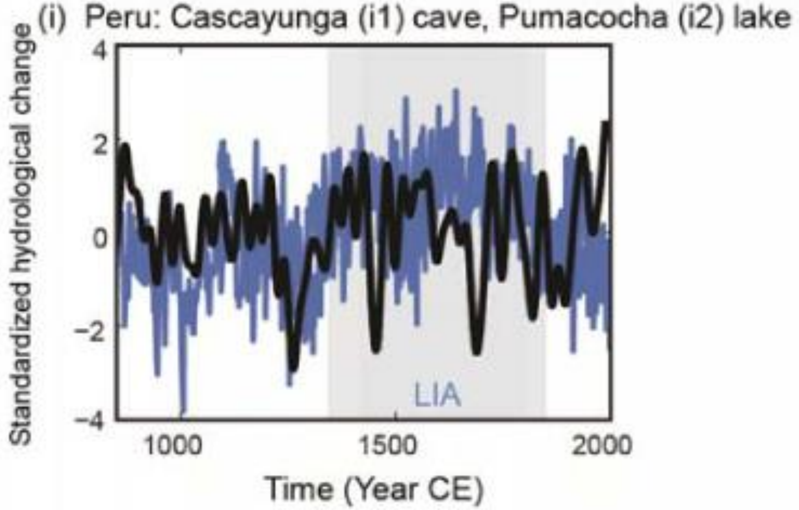
IPCC AR5 Historical and LM − Power spectrum

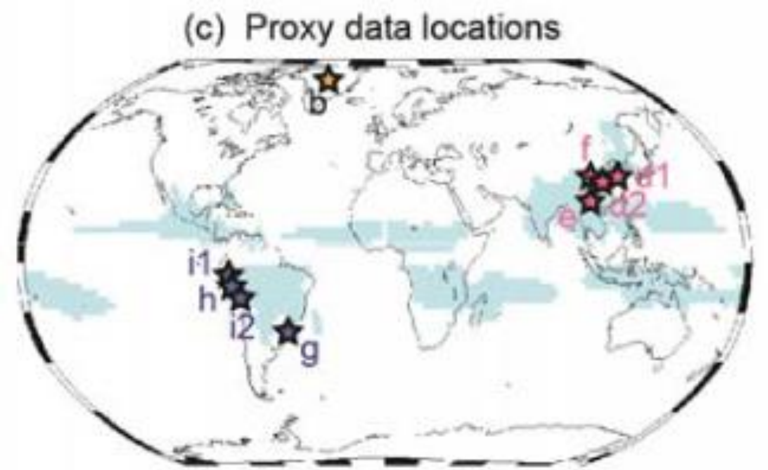


IPCC AR5 – Chapter 9 (2013)

IPCC AR5 LM − Hydrologic changes

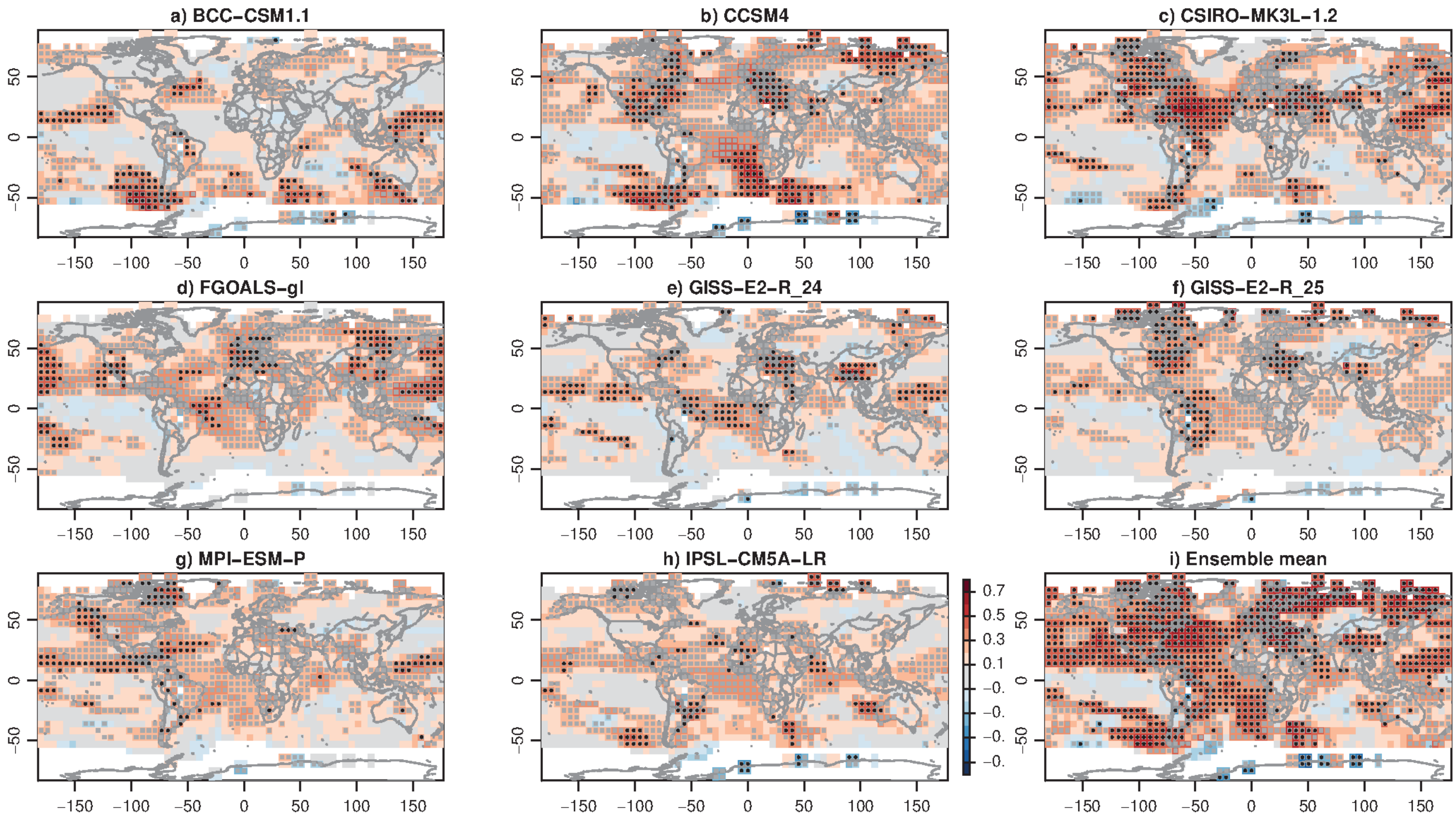






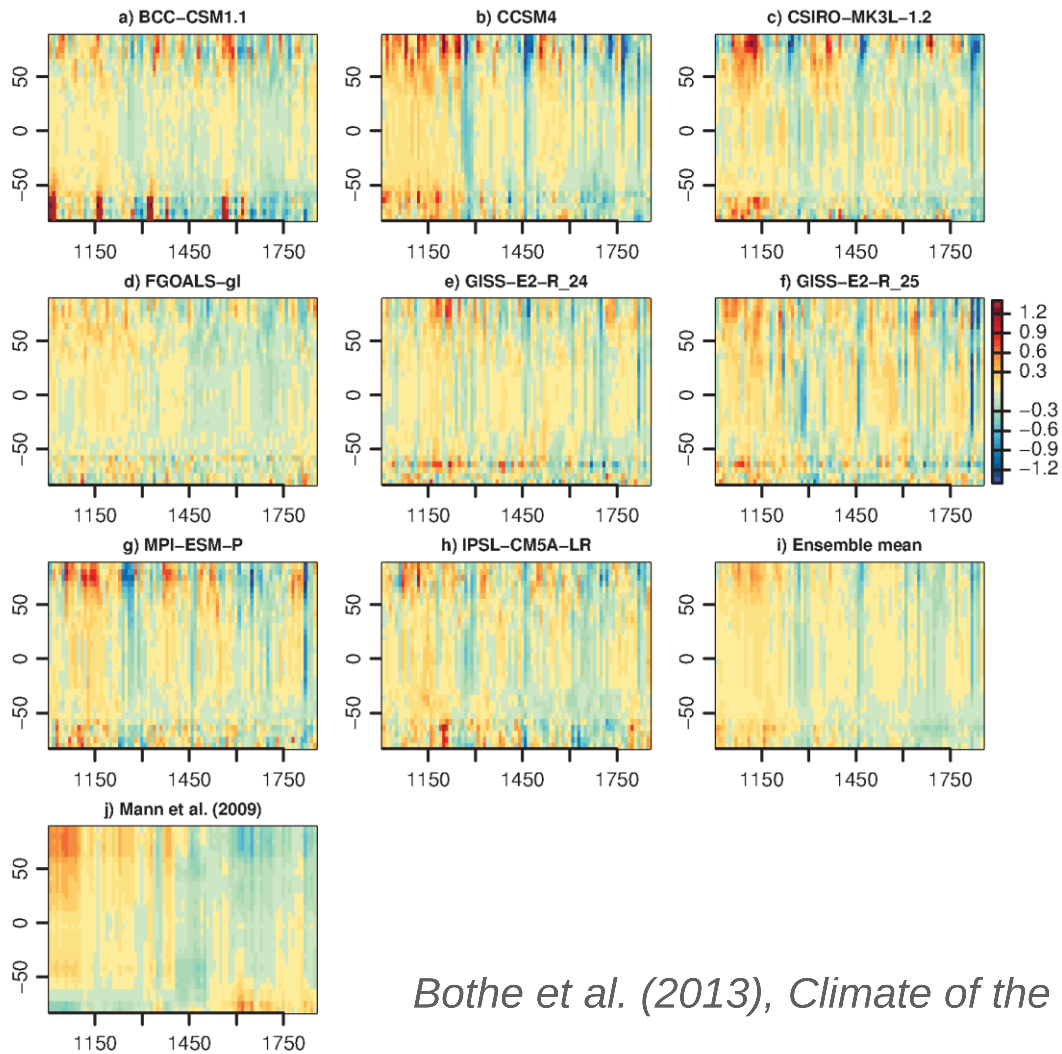
IPCC AR5 – Chapter 5 (2013)

Correlation of past1000 ensemble members with NH temperature



Bothe et al. (2013), Climate of the Past Discussions, 9, 3789-3824.

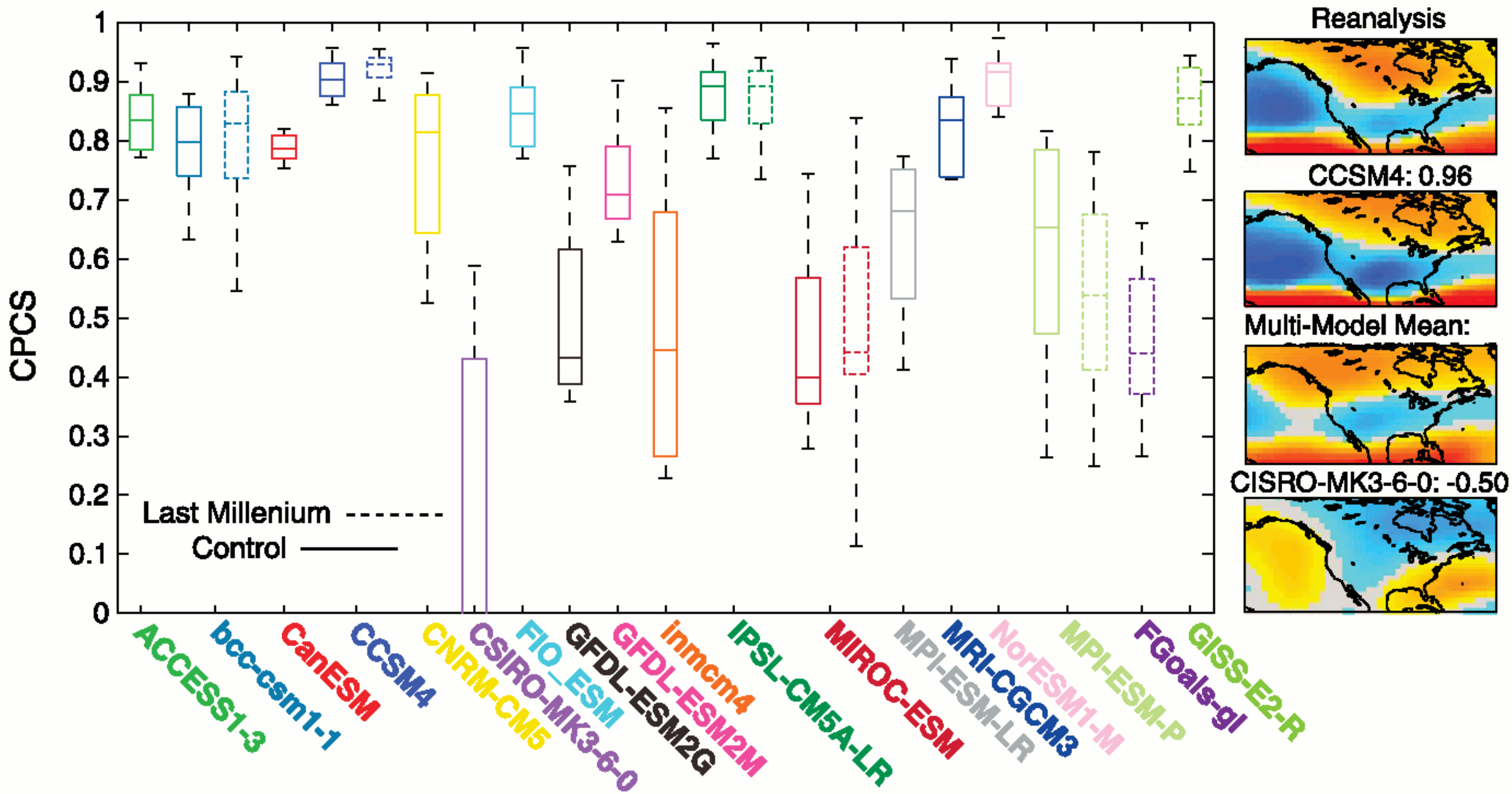
Evolution of zonal-mean temperature within the past1000 ensemble



- Individual ensemble members generally simulate relatively warm conditions, punctuated by short, volcanically-driven cool periods.
- Long-term cooling trend becomes more apparent in the ensemble mean.

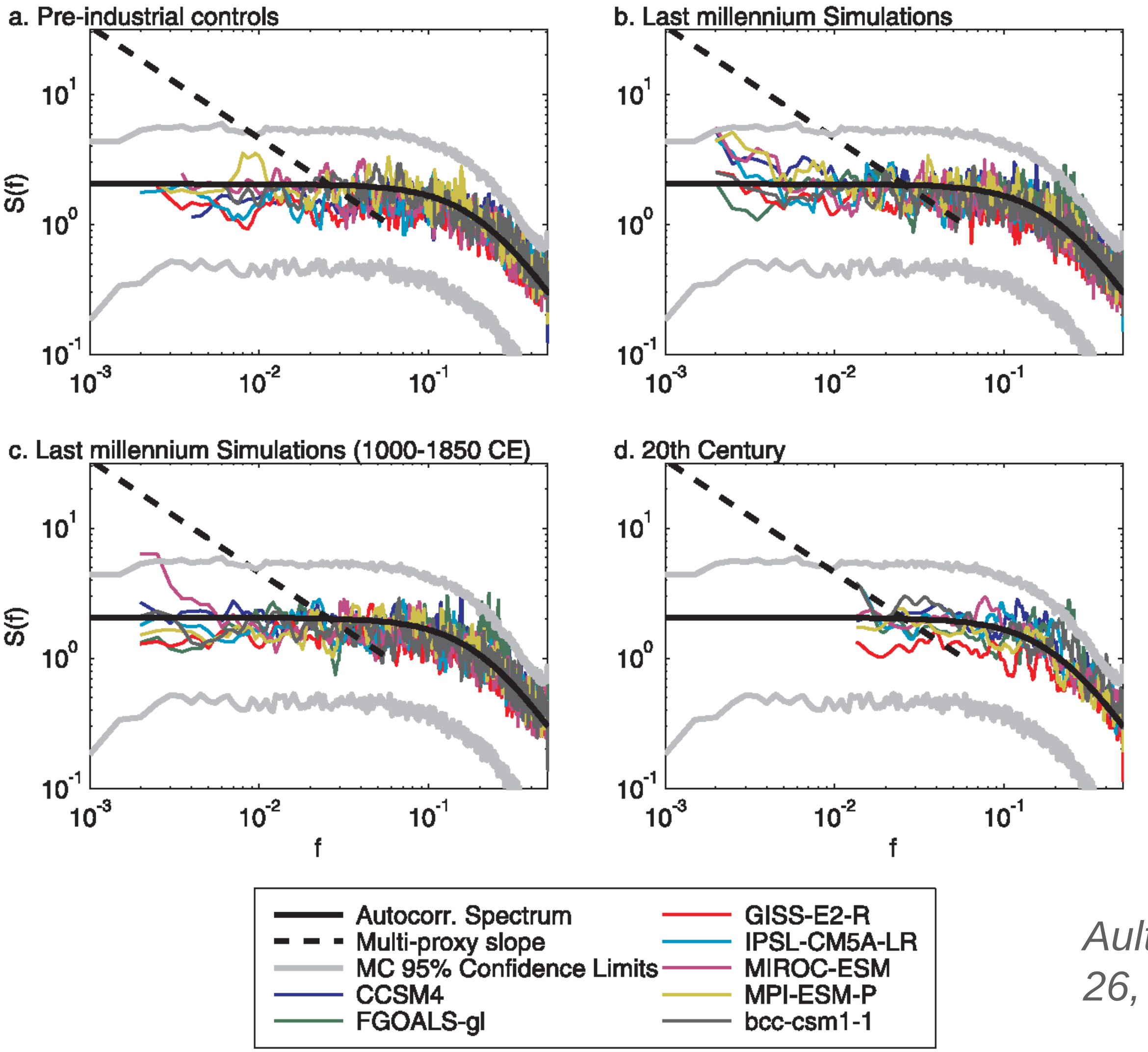
Bothe et al. (2013), Climate of the Past Discussions, 9, 3789-3824.

Stability of teleconnections in the past1000 ensemble



Coats et al. (2013), Geophysical Research Letters, 40, 4927-4932.

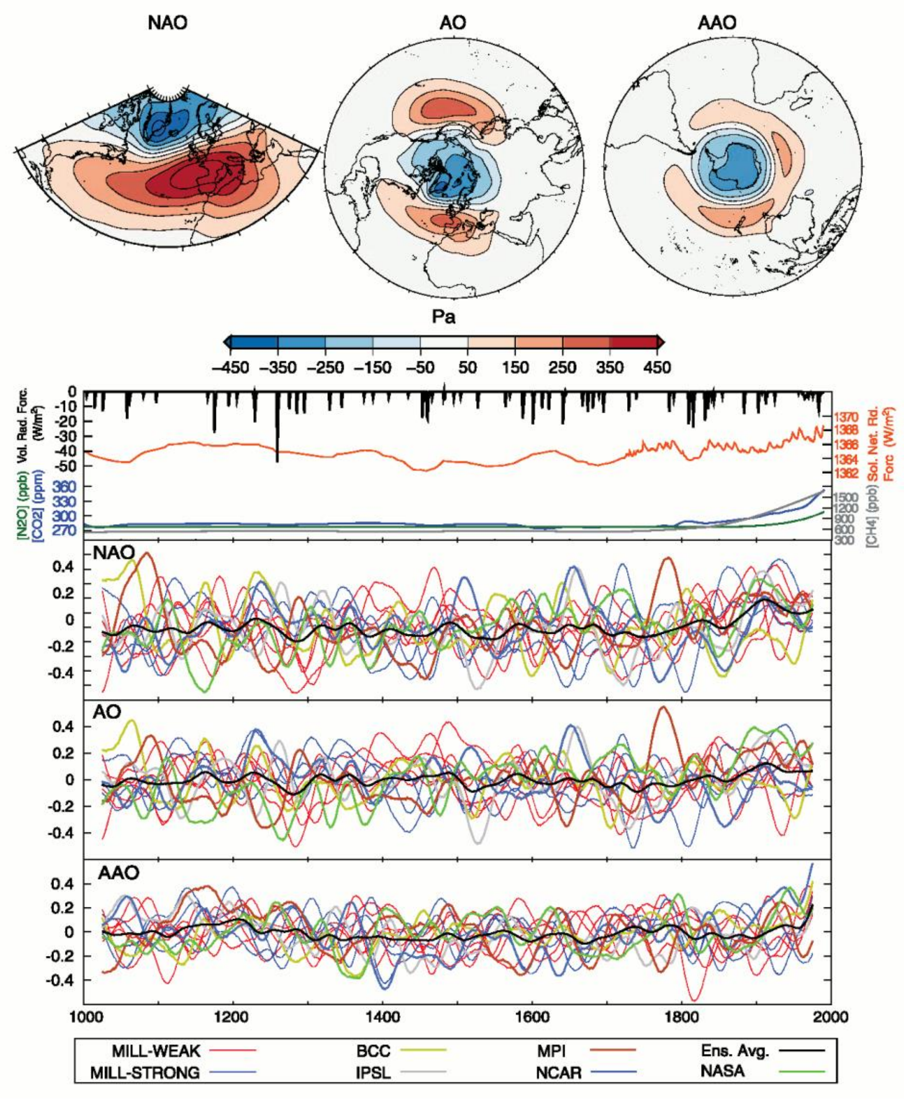
Spectrum of hydroclimate variability in the past1000 ensemble



- The spectra of the North American PDSI for the past1000 ensemble members are essentially indistinguishable from an AR(1) process.

Ault et al. (2013), Journal of Climate, 26, 5863-5878.

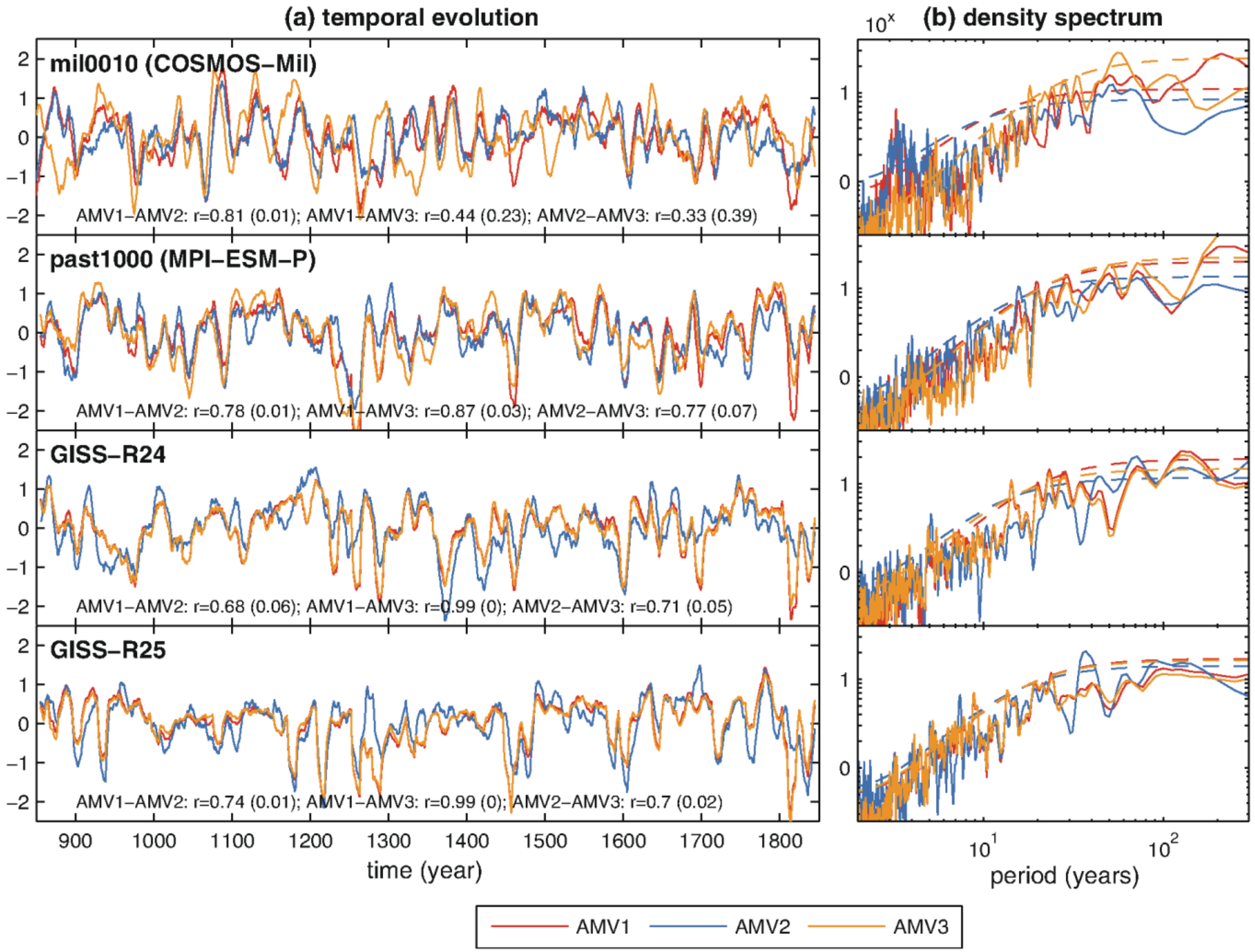
Variability in the annular modes within the past1000 ensemble



- The temporal evolution of each of the three modes appears to be incoherent between different members of the ensemble.
- At the 5% probability level, the null hypothesis that the evolution is dominated by internal variability cannot be rejected.

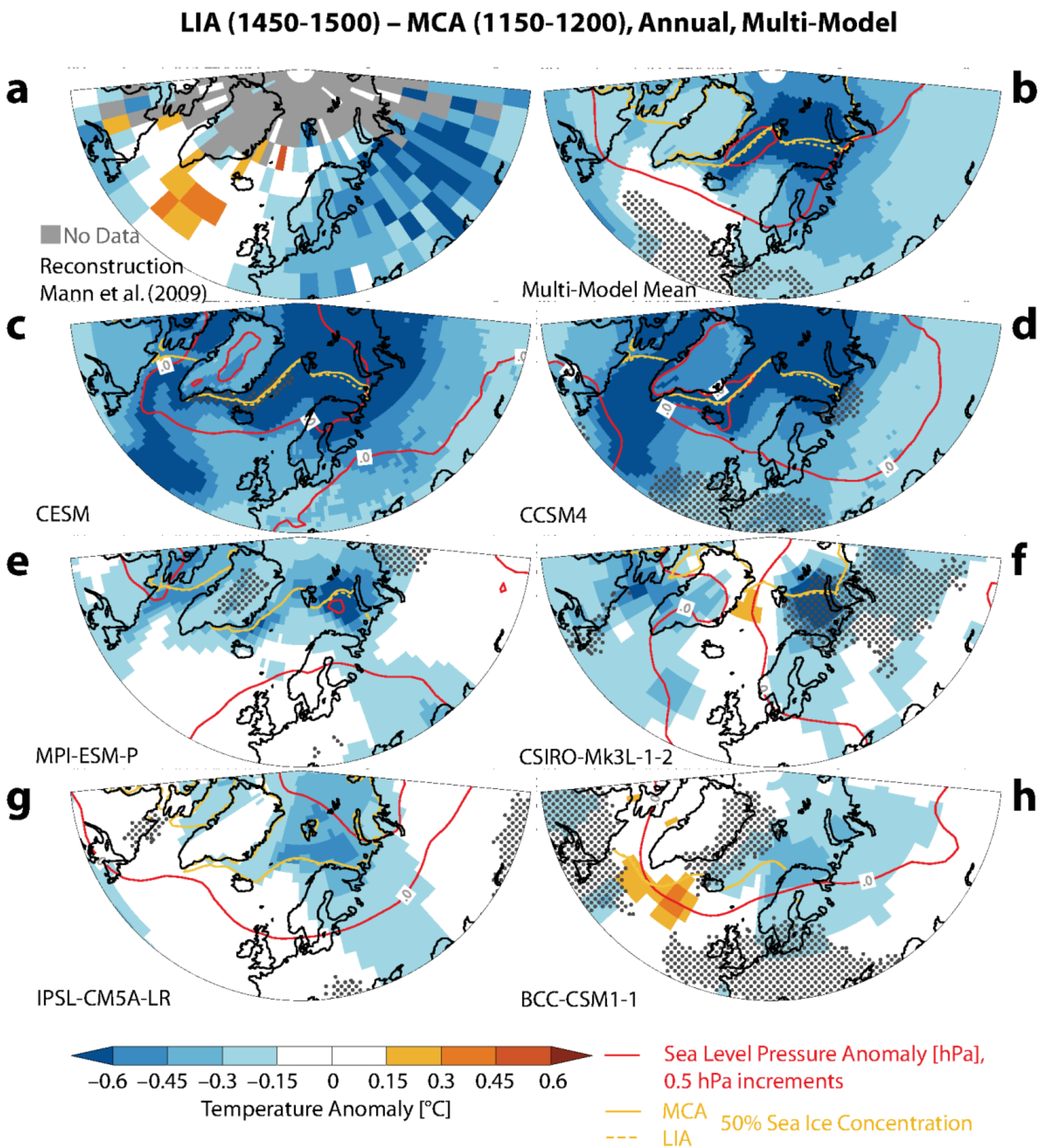
Gomez-Navarro and Zorita (2013), Geophysical Research Letters, 40, 3232-3236.

Atlantic Multidecadal Variability within the past1000 ensemble



Zanchettin et al. (in press), Climate Dynamics.

Feedbacks in the past1000 ensemble



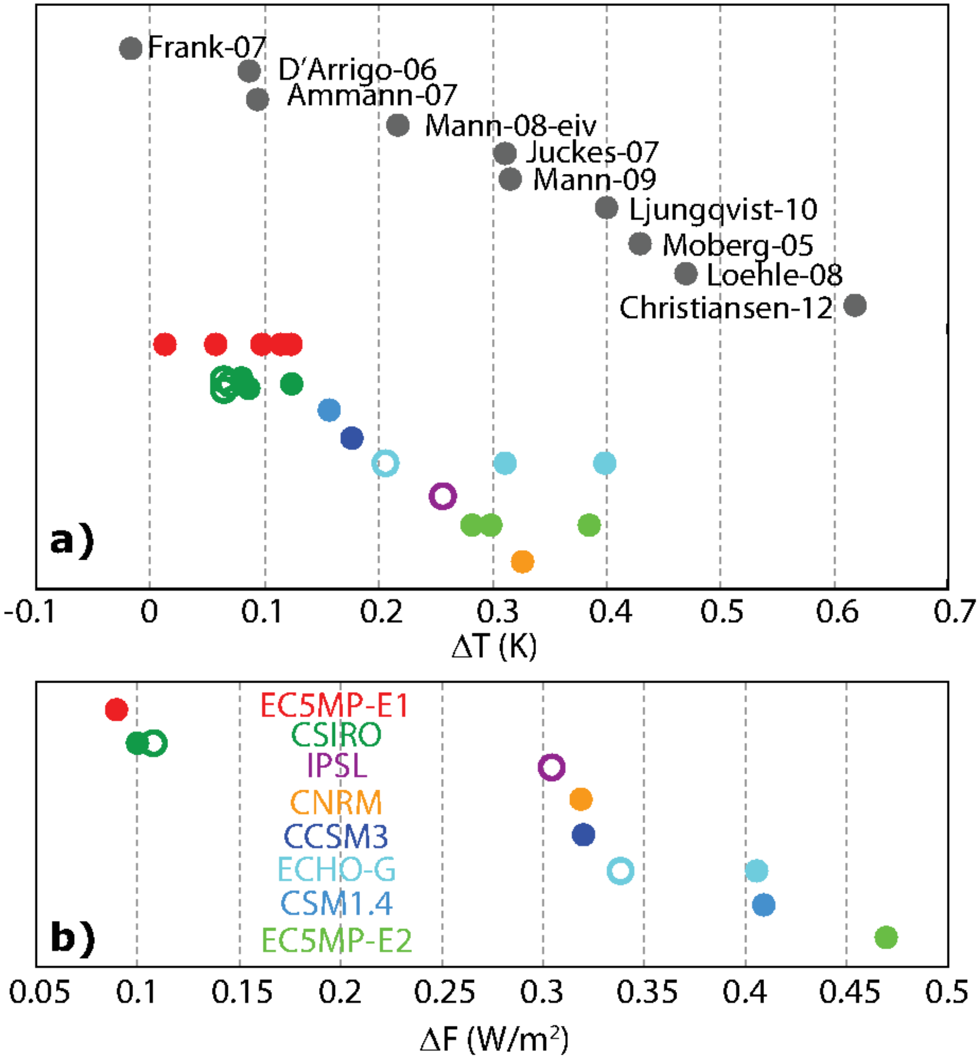
Flavio Lehner, PhD thesis

- Background to the last millennium simulations in IPCC and PMIP
- Overview of experimental design for PMIP3 − CMIP5
- PMIP3 − CMIP5 simulations
- Other modeling efforts
- Next steps: CMIP6 and next PMIP

Pre-PMIP3 simulations analysed in the IPCC AR5 WG1 report

Model	(No. runs) Period	Forcings[a]	Reference
Pre PMIP3/CMIP5 Experiments			
CCSM3	(1x) 1000–2000	$SS^{11} \cdot V^{22} \cdot G^{30,31,35}$	Hofer et al. (2011)
	(4x) 1500–2000		
CNRM-CM3.3	(1x) 1001–1999	$SS^{11} \cdot V^{21} \cdot G^{30,34,35} \cdot A^{44} \cdot L^{54}$	Swingedouw et al. (2011)
CSM1.4	(1x) 850–1999	$SS^{10} \cdot V^{21} \cdot G^{30,31,35} \cdot A^{41}$	Ammann et al. (2007)
CSIRO-MK3L-1-2	(3x) 1–2001	SW^{14}	Phipps et al. (2013)
	(3x) 1–2001	$SW^{14} \cdot G^{34} \cdot O^{70}$	
	(3x) 501–2001	$SW^{14} \cdot V^{24} \cdot G^{34} \cdot O^{70}$	
ECHAM4/OPYC	(1x) 1500–2000	$SS^{11} \cdot V^{21,26} \cdot G^{38} \cdot A^{42} \cdot L^{55}$	Stendel et al. (2006)
ECHAM5/MPIOM	(5x) 800–2005	$SW^{13} \cdot V^{25} \cdot G^{34,39} \cdot A^{40} \cdot L^{53} \cdot O^{61}$	Jungclaus et al. (2010)
	(3x) 800–2005	$SS^{10} \cdot V^{25} \cdot G^{34,39} \cdot A^{40} \cdot L^{53} \cdot O^{61}$	
ECHO-G	(1x) 1000–1990	$SS^{11} \cdot V^{20} \cdot G^{31,36,37}$	González-Rouco et al. (2003)[b]
	(1x) 1000–1990	$SS^{11} \cdot V^{20} \cdot G^{31,36,37}$	Gonzalez-Rouco et al. (2006)
	(2x) –7000–1998	$SS^{12} \cdot G^{30} \cdot O^{62}$	Wagner et al. (2007)
HadCM3	(1x) 1492–1999	$SS^{11} \cdot V^{23} \cdot G^{32} \cdot A^{43} \cdot L^{50,54,55} \cdot O^{60}$	Tett et al. (2007)
IPSLCM4	(1x) 1001–2000	$SS^{11} \cdot G^{30,34,35} \cdot A^{44} \cdot O^{63}$	Servonnat et al. (2010)
FGOALS-gl	(1x) 1000–1999	$SS^{11} \cdot V^{20} \cdot G^{30,31,35}$	Zhou et al. (2011)[c]

MCA-LIA transition in the pre-PMIP3 simulations



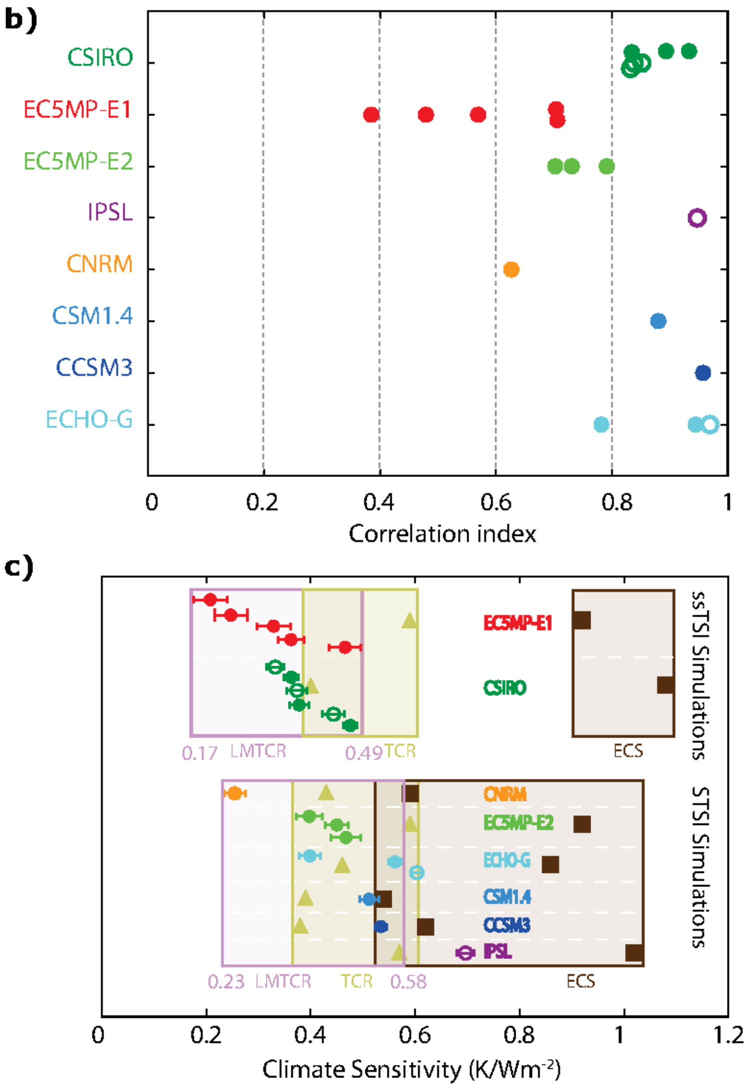
- For each simulation, the temperature change can be directly related to the change in radiative forcing.

- Simulations that use solar forcing with weaker changes in amplitude exhibit weaker temperature changes.

- Intra-model variability can be larger than inter-model differences, suggesting a major role of internal variability.

Fernandez-Donado et al. (2013), Climate of the Past, 9, 393-421.

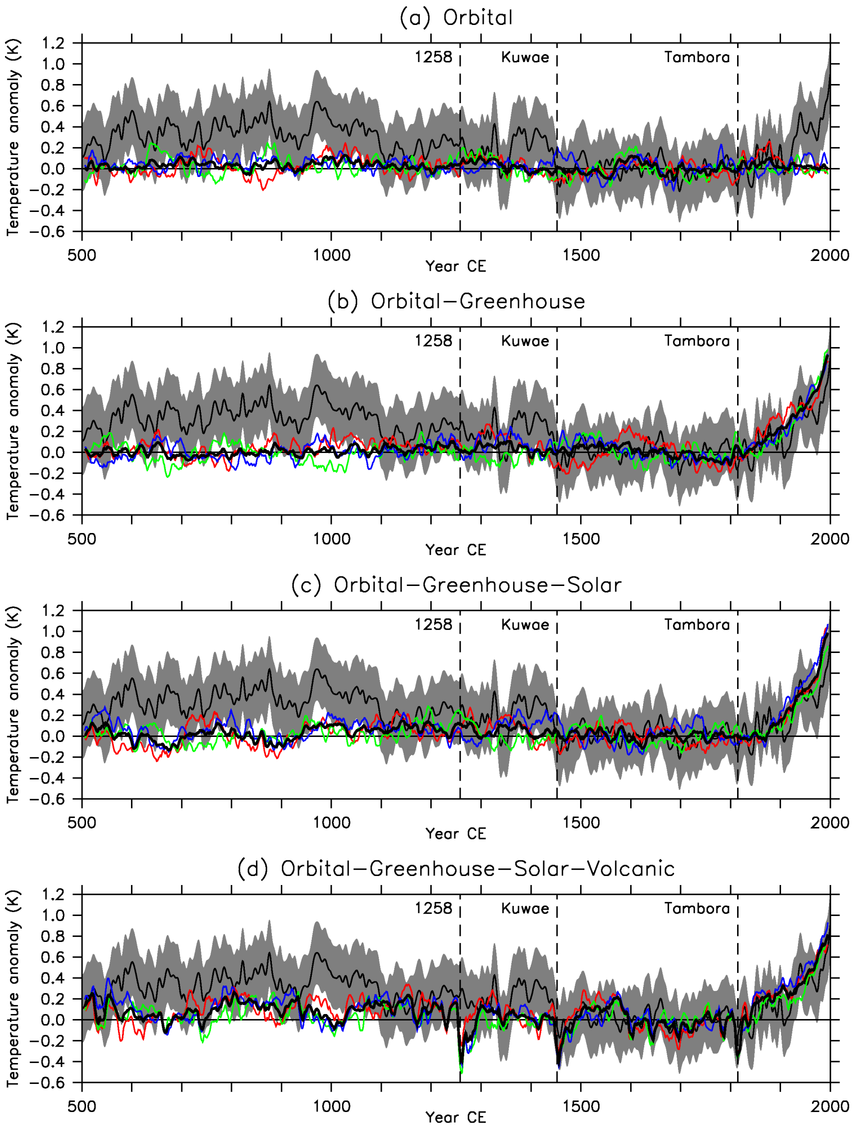
Estimating transient climate response using the pre-PMIP3 simulations



- The simulations are generally strongly correlated with external forcing
- The relationship between the forcing and the temperature response allows a "Last Millennium Transient Climate Response" to be calculated. This describes the instantaneous response to external forcing.
- LMTCR is smaller than ECS, but the range overlaps with the range of TCR.
- Intra-model variability can again be large.

Fernandez-Donado et al. (2013), Climate of the Past, 9, 393-421.

Adding external forcings sequentially



- Individual forcings are progressively added to an ensemble of climate model simulations.
- Orbital forcing by itself gives no long-term trend. The addition of GHGs causes the model to reproduce the observed warming since the 19^{th} century.
- Solar forcing introduces weak centennial-scale variability.
- Volcanic forcing introduces stronger decadal-scale variability.

Phipps et al. (2013), Journal of Climate, 26, 6915-6936.

The role of the carbon cycle

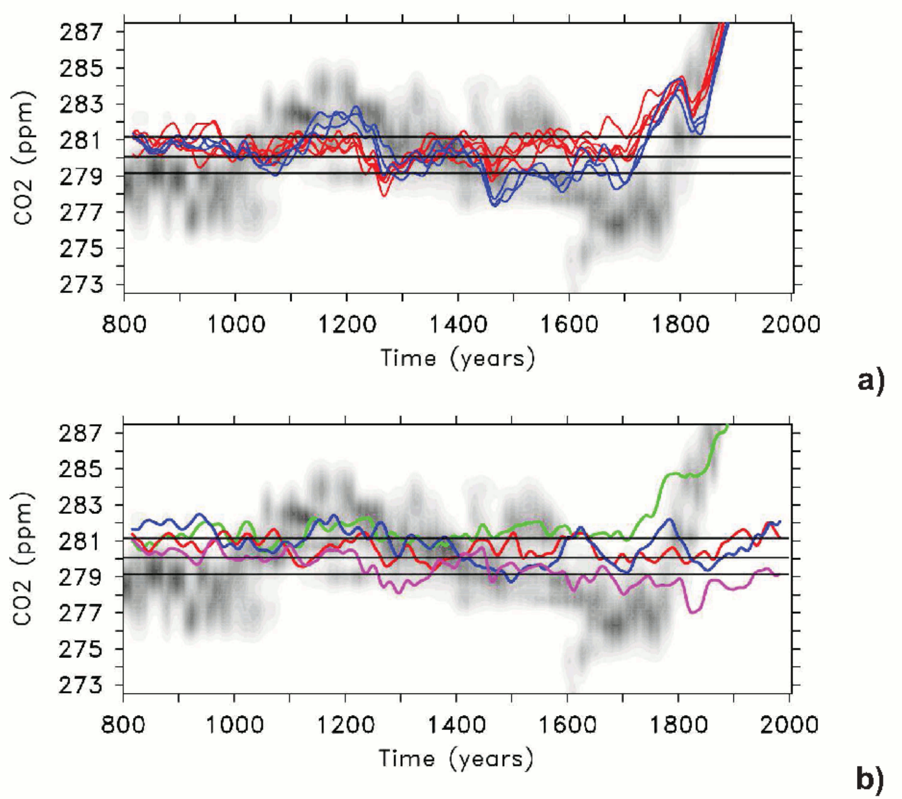


Fig. 6. CO_2 concentrations (31-year running mean) from **(a)** ensembles E1 (red) and E2 (blue) in comparison with a compilation of ice core reconstructions (grey shading, see Appendix A). Black horizontal lines denote the control experiment mean and its 5th–95th percentile range, **(b)** the respective CO_2 concentrations from the experiments forced by one single component, i.e. standard solar forcing (red), strong solar forcing (blue), land-cover change (green), and volcanic aerosols (purple).

- MPI Earth System Model with fully interactive carbon cycle. Two different ensembles using different reconstructions of solar forcing.

- When driven with all natural and anthropogenic forcings, the CO2 concentration is relatively stable over the pre-industrial era.

- Individual forcings have competing effects on the carbon budget.

Jungclaus et al. (2010), Climate of the Past, 6, 723-737.

Application of individual forcings

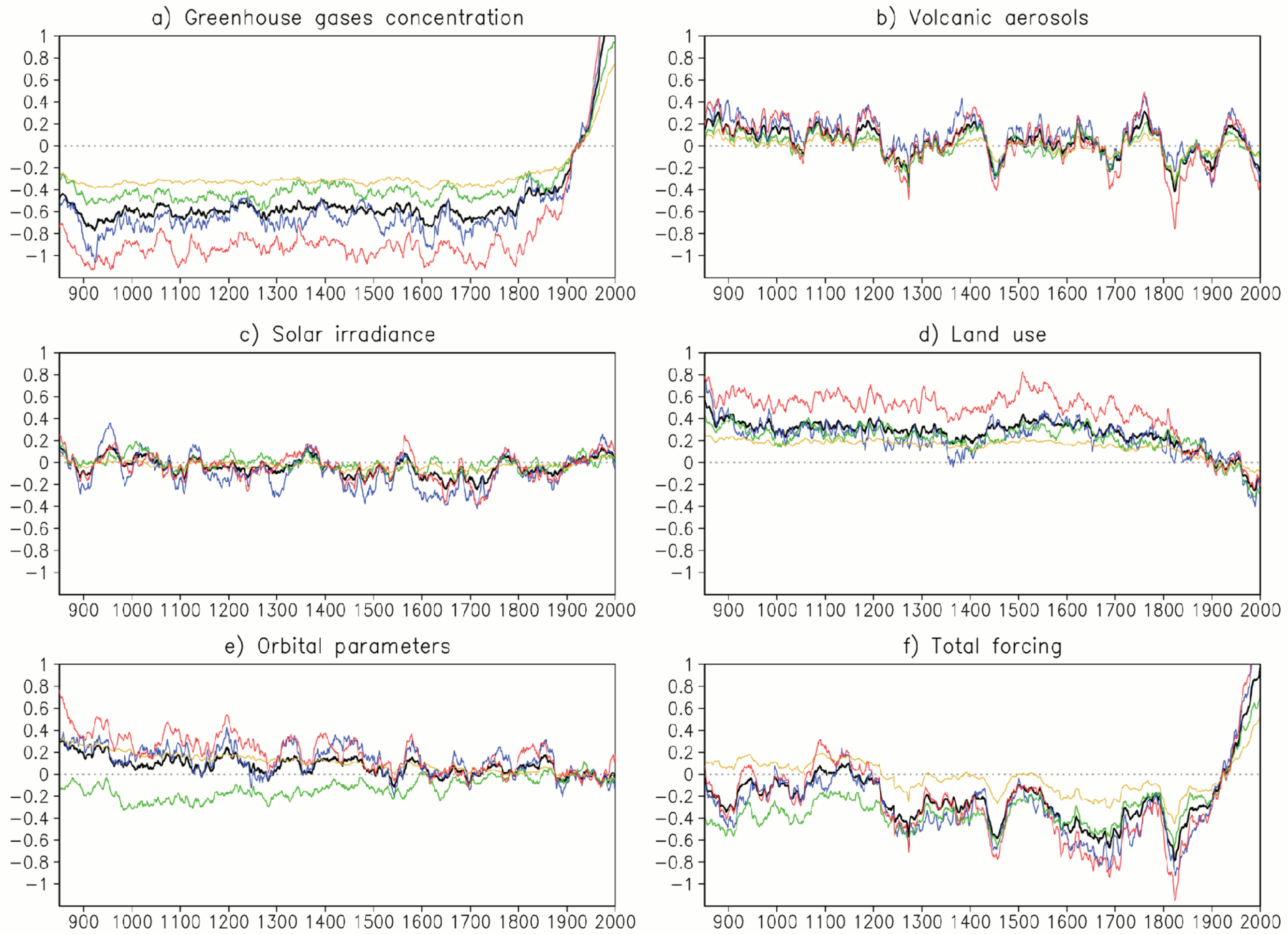


Figure 1. Anomaly in annual and seasonal mean surface temperature (°C) in the Arctic (north of 64°) over the last 1150 years as simulated by LOVECLIM in response to different forcings. Each time series represents the mean of an ensemble of ten simulations. The annual mean is displayed in black, the winter (JFM) in blue, the spring (AMJ) in green, the summer (JAS) in yellow, and the autumn (OND) in red. The reference period is AD 1850–1980. A 31year running mean has been applied to the time series. Colour figure available online.

Crespin et al. (2013), The Holocene, 23, 321-329.

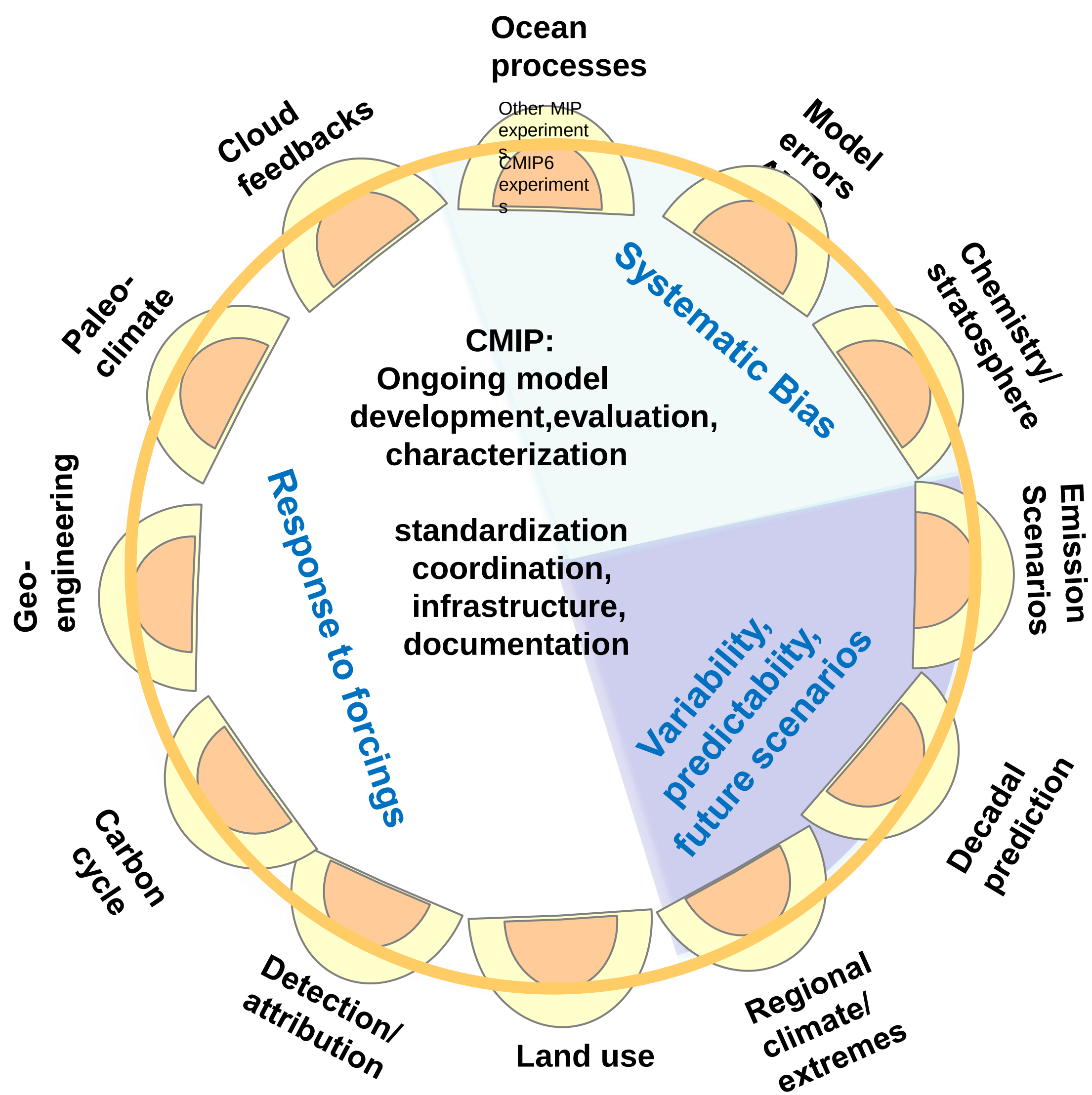
Contribution of individual forcings to regional temperature trends

Table S4 | Simulated annual mean temperature trends related to individual forcings in LOVECLIM from 900-1850 CE (°C ka^{-1}).

Region	Orbital	Solar	Volcanic	Land use	GHG	All forcings	Uncertainty
Arctic	-0.12	-0.11	-0.15	-0.10	0.04	-0.42	0.07
Europe	-0.05	-0.07	-0.11	-0.02	0.04	-0.23	0.00
Asia	0.01	-0.05	-0.11	-0.13	0.03	-0.23	0.01
North America	-0.01	-0.12	-0.08	-0.05	0.08	-0.21	0.00
Australia	0.04	-0.03	-0.05	-0.03	0.02	-0.07	0.01
South America	0.05	-0.02	-0.04	-0.03	0.01	-0.04	0.02
Antarctica	-0.05	-0.02	-0.07	-0.05	0.06	-0.20	0.02
Global (land)	-0.01	-0.05	-0.09	-0.05	0.03	-0.17	0.00

PAGES 2k Consortium (2013), Nature Geoscience, 6, 339-346.

Next Steps: PMIP and CMIP6



WCRP Grand Challenges

- Clouds, circulation and climate sensitivity
- Changes in cryosphere
- Climate extremes
- Regional climate information
- Regional sea-level rise
- Water availability

PMIP6: Experimental design

- LM Ensembles?
- LM single forcing experiments?
- 850-1850AD? 850-2013AD? 0-2013AD?
- Ensembles for LM active periods of volcanic eruptions; solar min/max?