Annex II: Paleoclimate

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AII.1 Introduction to the Paleo Data Annex

This Annex documents the paleoclimate and long-term forcing datasets used by Working Group I in the Sixth Assessment Report. The bibliographic citations and data citations (URL or DOI links to digital data) listed in the table provide a traceable account of the studies and data that form the basis of the confidence-likelihood statements associated with the assessments of paleoclimate, or that were used by WG 1 authors to calculate new values used in this report. The table lists variables that measure changes in the atmosphere, hydrosphere, ocean, cryosphere and biosphere. It includes summary statistics that quantify each of the paleoclimate variables during multiple periods. The periods include those under investigation by the Paleoclimate Model Intercomparison Project (PMIP), and other reference periods used in AR6 (Box 1.3), namely:

PETM — Palaeocene-Eocene thermal maximum (55.5-55.3 Ma)
EECO — early Eocene climate optimum (52-50 Ma)
PPWP — mid-Piacenzian warm period (late Pliocene, 3.3-3.0 Ma)
LIG — last inter-glaciation (129-116 ka or 127 ka peak)
LGM — last glacial maximum (21-19 ka)
LDG — last deglaciation (18-11 ka)
MH — mid-Holocene (6 ka)
MCA — medieval climate anomaly (950-1250 CE)
LIA — little ice age (1450-1850 CE)
EI — early industrial (1850-1900 CE)
P — present (1995-2014)

[FOD note: The purpose and scope of this Annex is under discussion by cross-chapter paleoclimate authors and will be revisited during LAM3. Input from expert reviewers on the perceived utility of the Annex, and its expected or ideal content, is welcome at this early stage. This version of the Annex is incomplete and preliminary. It primary includes datasets described in Chapter 2, "Changing State of the Climate System." Some bibliographic citations and most data citations are missing. The table will likely be subdivided by either time period or by major Earth sphere].

Period	**Spatial scale**	**Climate variable**	**Metric**	**Units**	**Value**	**Uncer tainty**	**Data citation (DOI/URL)**	**Reference**	**Note & Figure #**
PETM	global	atmo - CO2 concentration	rate of change	ppm/ 100 yr	30	0.3-100		middle estimate (between 3000 and 20,000 yr duration) Foster email 3/27/19	Fig. 2.2; ref for duration: (Gingerich, 2019)
PETM	global	atmo - CO2 concentration	average	ppm	2200	+1900 -700		(Gutjahr et al., 2017)	Fig. 2.2
EECO	global	atmo - CO2 concentration	average	ppm	1150	-289, +443		(Anagnostou et al., 2016, 2019)	Fig. 2.2; 95% uncertainty
MPWP	global	atmo - CO2 concentration	average	ppm	369	-37, +27		(de la Vega et al., 2019)	Fig. 2.2; 95% uncertainty
MPWP	global	atmo - CO2 concentration	average	ppm	366	± 42		(Martínez-Botí et al., 2015a; Haywood et al., 2016)	Fig. 2.2
LIG	global	atmo - CO2 concentration	average	ppm	276	± 4		(Bereiter et al., 2015)	Fig. 2.2, 2.3
LGM	global	atmo - CO2 concentration	average	ppm	191	± 4		(Bereiter et al., 2015)	Fig. 2.2, 2.3
LDG	global	atmo - CO2 concentration	rate of change, max	ppm/ 100 yr	13	± 1		(Marcott et al., 2014)	
MH	global	atmo - CO2 concentration	average	ppm	265	± 3		(Bereiter et al., 2015)	Fig. 2.3

MCA	global	atmo - CO2 concentration	average	ppm	283	± 3		(Bereiter et al., 2015)	Fig. 2.3
LIA	global	atmo - CO2 concentration	average	ppm	281	± 4		(Bereiter et al., 2015)	Fig. 2.3
EI	global	atmo - CO2 concentration	average	ppm	290	± 4		(Bereiter et al., 2015)	Fig. 2.4
EI	global	atmo - CO2 concentration	average	ppm	289.1	± 1.6		(Meinshausen et al., 2017)	Fig. 2.4
EI	global	atmo - CO2 concentration	rate of change	ppm/ 100 yr	22.4			(Meinshausen et al., 2017)	
LIG	global	atmo - CH4 concentration	average	ppb	649	± 41		(Loulergue et al., 2008)	Fig. 2.3; 116-128.5 ka
LGM	global	atmo - CH4 concentration	average	ppb	382	± 10		(Mitchell et al., 2011; Rhodes et al., 2013; Marcott et al., 2014; WAIS Divide Project Members. et al., 2015)	Fig. 2.3
LDG	Global	atmo - CH4 concentration	rate of change	ppb/ 100 yr	200	± 2		(Rhodes et al., 2015)	check uncertainty
MH	global	atmo - CH4 concentration	average	ppb	592	± 16		(Mitchell et al., 2011; Rhodes et al., 2013; Marcott et al., 2014; WAIS Divide Project Members. et al., 2015)	Fig. 2.3
MCA	global	atmo - CH4 concentration	average	ppb	697	± 10		(Mitchell et al., 2013)	Fig. 2.3
LIA	global	atmo - CH4 concentration	average	ppb	724	± 26		(Mitchell et al., 2013)	Fig. 2.3
EI	global	atmo - CH4 concentration	average	ppb	862	± 6		(Meinshausen et al., 2017)	Fig. 2.3
EI	global	atmo - CH4 concentration	rate of change	ppb/ 100 yr	234.3			(Meinshausen et al., 2017)	
LIG	global	atmo - N2O concentration	average	ppb	262	± 7		(Flückiger et al., 2004; Schilt et al., 2010, 2014)	Fig. 2.3; 116-128.5 ka
LGM	global	atmo - N2O concentration	average	ppb	209	± 7		(Flückiger et al., 2004; Schilt et al., 2010, 2014)	Fig. 2.3
EI	global	atmo - N2O concentration	average	ppb	276.4	± 4		(Meinshausen et al., 2017)	Fig. 2.3
EI	global	atmo - N2O concentration	rate of change	ppb/ 100 yr	12.7			(Meinshausen et al., 2017)	
MH	N Africa / N Atlantic	atmo - dust emissions	relative to 2-0 ka BP	factor	3	2-5		(McGee et al., 2013; Williams et al., 2016; Hayes et al., 2017; Middleton et al., 2018)	based on ensemble of marine sediment records
MH	global	atmo - dust emissions	relative to 2-0 ka BP	factor	0.91			(Albani et al., 2015)	based on one model tuned to global dataset
PETM	global	atmo - temperature, annual	anomaly wrt modern (14°)	°C	19	± 4		(Hollis et al., 2019) Hollis email 3/28/19	based on method by (Caballero and Huber, 2013)
EECO	global	atmo - temperature, annual	anomaly wrt EI (14°)	°C	15			(Hollis et al., 2019) Hollis email 3/28/19	based on method by (Caballero and Huber, 2013)

EECO	global	atmo - temperature, annual	anomaly wrt modern	°C	13	± 3		(Caballero and Huber, 2013)	
MPWP	global	atmo - temperature, annual	anomaly wrt EI	°C	3.8	± 0.8		(Fischer et al., 2018)	Scaled Martinez-Boti's estimate of SST (x1.6)
LIG	global	atmo - temperature, annual	anomaly wrt EI	°C	0.8	± 0.5		(Fischer et al., 2018)	Scaled Hoffman's estimate of SST (x1.6)
LIG	global	atmo - temperature, annual	anomaly wrt 5-0 ka	°C	2	0.4–3.6		(Snyder, 2016)	Fig. 2.10
LGM	land	atmo - temperature, annual	anomaly wrt ??	°C	-6	± 1		(Harrison et al., 2015)	
LGM	global	atmo - temperature, annual	anomaly wrt 5-0 ka	°C	-6.2	-4.5–-8.1		(Snyder, 2016)	Fig. 2.10
LGM	global	atmo - temperature, variability	wrt Holocene	factor	4.4	2.5-6.6		(Rehfeld et al., 2018)	uncertainty = 90% c.i.
Holocene	Antarctica	atmo - temperature	τc (climate transition scale)	yr	3000	± 1000		(Lovejoy et al., 2013)	time-scale at which 20C temperature exceed the amplitude of long-term fluctuations
Holocene	N Hemi	atmo - temperature	τc (climate transition scale)	yr	100	± 50		(Lovejoy et al., 2013)	time-scale at which 20C temperature exceed the amplitude of long-term fluctuations
MH	sea surface	atmo - temperature, annual	anomaly wrt ??	°C	0.2	± 0.2		(Harrison et al., 2015)	area-weighted
MH	land	atmo - temperature, annual	anomaly wrt EI	°C	0			(Harrison et al., 2015)	area-weighted
MH	global	atmo - temperature, annual	anomaly wrt 1961-1990	°C	0.35	± 0.14		(Marcott et al., 2013)	Fig. 2.10; 1 SD
MH	N America	atmo - temperature, annual	anomaly wrt 1917-2016	°C	0			(Marsicek et al., 2018)	
MH	Europe	atmo - temperature, annual	anomaly wrt 5 ka	°C	0.5-0.7			(Marsicek et al., 2018)	
MH	70-90°N latitude	atmo - temperature, annual	anomaly wrt 1850-1950	°C	1.5	0.8-2.7	https://www.ncdc.noaa.gov/paleo-search/study/25890	(Routson et al., 2019)	95% uncertainty; 5.7-6.3 ka
MH	50-70° N latitude	atmo - temperature, annual	anomaly wrt 1850-1950	°C	1.0	0.5-1.4	https://www.ncdc.noaa.gov/paleo-search/study/25890	(Routson et al., 2019)	95% uncertainty; 5.7-6.3 ka
MH	30-50° N latitude	atmo - temperature, annual	anomaly wrt 1850-1950	°C	0.5	-0.1-1.0	https://www.ncdc.noaa.gov/paleo-search/study/25890	(Routson et al., 2019)	95% uncertainty; 5.7-6.3 ka

MH	10-30° N latitude	atmo - temperature, annual	anomaly wrt 1850-1950	°C	0.1	-0.9-1.2	https://www.ncdc.noaa.gov/paleo-search/study/25890	(Routson et al., 2019)	95% uncertainty; 5.7-6.3 ka
MH	10°S-10°N latitude	atmo - temperature, annual	anomaly wrt 1850-1950	°C	0.2	-0.6-0.9	https://www.ncdc.noaa.gov/paleo-search/study/25890	(Routson et al., 2019)	95% uncertainty; 5.7-6.3 ka
MH	N Hemphere	atmo - temperature, annual	latitudinal gradient	°C/°latitude	-0.491	± 0.007		(Routson et al., 2019)	± SD; 5.7-6.3 ka
MCA	global	atmo - temperature, annual	colder than 1951-2000	% of ensemble members	99.0			(PAGES 2k Consortium , in revision)	
MCA	global	atmo - temperature, annual	anomaly wrt EI	°C	0.14	-0.05–0.26		(PAGES 2k Consortium , in revision)	Fig. 2.10
LIA	global	atmo - temperature, annual	anomaly wrt EI	°C	-0.03	-0.30–0.06		(PAGES 2k Consortium , in revision)	Fig. 2.10
CE – 50 yr max	global	atmo - temperature, annual	rate of change	°C/100 yr	0.96			(PAGES 2k Consortium , in revision)	
1951-2000	global	atmo - temperature, annual	warmest 50 yr period of CE	% of ensemble members	74.8			(PAGES 2k Consortium , in revision)	
1968-2017	global	atmo - temperature, annual	highest 50 yr rate of change of CE	% of ensemble members	96.4			(PAGES 2k Consortium , in revision)	
1968-2017	global	atmo - temperature, annual	rate of change	°C/100 yr	1.76			(PAGES 2k Consortium , in revision)	
EI	N Hemi	atmo - temperature, annual	latitudinal gradient	°C/°latitude	-0.506	± 0.002		(Routson et al., 2019)	± SD; 1850-1910
P	N Hemi	atmo - temperature, annual	latitudinal gradient	°C/°latitude	-0.495			(Routson et al., 2019)	
LDG	Europe	bio - forest turnover	squared chord dissimilarity	unitless	0.15-0.30			(Seddon et al., 2015)	
LDG	E NAm	bio - forest turnover	squared chord dissimilarity	unitless	0.15-0.60			(Williams et al., 2004; Shuman, 2012)	
MH/Holocene	Europe	bio - forest turnover	squared chord dissimilarity	unitless	0 - 0.10			(Seddon et al., 2015)	
MH/Holocene	E NAm	bio - forest turnover	squared chord dissimilarity	unitless	0.05-0.25			(Williams et al., 2004; Shuman, 2012)	
EI	Europe	bio - forest turnover	squared chord dissimilarity	unitless	0.15-0.35			(Seddon et al., 2015)	
EI	E NAm	bio - forest turnover	squared chord dissimilarity	unitless	0.05-0.25			(Williams et al., 2004; Shuman, 2012)	
EECO	N Hemi	bio - northern treeline	latitude	°N	78	75-81			
MPWP	N Hemi	bio - northern	latitude	°N	78	75-81		(Salzmann et al., 2008)	based on biome map

		treeline							
LGM	N Hemi	bio - northern treeline	latitude	°N	62	60-65		(Williams et al., 2011; Binney et al., 2017)	
MH	N Hemi	bio - northern treeline	latitude	°N	75	74-76		(Binney et al., 2017)	
MCA	N Hemi	bio - northern treeline	latitude	°N	71	70-72		(Binney et al., 2017)	
LIA	N Hemi	bio - northern treeline	latitude	°N	71	70-72		(Binney et al., 2017)	
EI	Eurasia	bio - northern treeline	latitude	°N	71			(Binney et al., 2009)	
MH	Europe	bio/forcing - open land cover	mean	%	14	± 5		(Marquer et al., 2017)	5.7-6.2 ka
MCA	Europe	bio/forcing - open land cover	mean	%	43	± 10		(Marquer et al., 2017)	
LIA	Europe	bio/forcing - open land cover	mean	%	48	± 10		(Marquer et al., 2017)	
historic (post 1850)	Europe	bio/forcing - open land cover	mean	%	40	± 10		(Marquer et al., 2017)	
MCA	global	forcing - stratospheric aerosol optical depth	average	unitless	0.012	± 0.004		(Toohey and Sigl, 2017)	35% uncertainty from Hegerl et al., 2006
LIA	global	forcing - stratospheric aerosol optical depth	average	unitless	0.017	± 0.006		(Toohey and Sigl, 2017)	Fig. 2.1; 35% uncertainty from Hegerl et al., 2006
EI	global	forcing - stratospheric aerosol optical depth	average	unitless	0.011	± 0.004		(Toohey and Sigl, 2017)	Fig. 2.1; 35% uncertainty from Hegerl et al., 2006
EI	global	forcing - stratospheric aerosol optical depth	average	unitless	0.010	± 0.003		Luo et al., in prep; CMIP6 historical forcing	Fig. 2.1
MH	global	forcing - total solar irradiance	average	W m^{-2}	1361.0	± 0.6		(Jungclaus et al., 2017; Wu, C. J. et al., 2018)	Fig. 2.1; 6.1-5.9 ka
MCA	global	forcing - total solar irradiance	average	W m^{-2}	1360.9	± 0.6		(Jungclaus et al., 2017; Matthes et al., 2017; Wu, C. J. et al., 2018)	Fig. 2.1
LIA	global	forcing - total solar irradiance	average	W m^{-2}	1360.7	± 0.6		(Jungclaus et al., 2017; Matthes et al., 2017; Wu, C. J. et al., 2018)	Fig. 2.1
EI	global	forcing - total solar irradiance	average	W m^{-2}	1361.0	± 0.6		(Jungclaus et al., 2017; Matthes et al., 2017; Wu, C. J. et al., 2018)	Fig. 2.1
MH	global high elevati on	cryo - glacier	size	relative to EI	smaller			(Solomina et al., 2015)	Fig. 2.25
MPWP	subtrop ics and mid latitude	hydro - E-P	relative to 20C	NA	wetter			Burls and Federov, 2017; Prentice et al., 2017	
MPWP	global -	hydro -	relative	NA	stronge			(Pound et al.,	N Africa,

	land	monsoon	to 20C		r			2014) Li et al., 2018; Yang et al., 2018	Asia, N Australia, Central America, and E SAm
LGM	global - land	hydro - monsoon	relative to 20C	NA	weaker			(Jiang et al., 2015; Fornace et al., 2016; Chevalier et al., 2017; Novello et al., 2017)	uncertainty in S SAm and S Africa
LGM	mid latitude land	hydro - P, humidity	relative to 20C	NA	drier			(Scheff et al., 2017)	
LGM	mid latitude land	hydro - soil moisture	relative to 20C	NA	wetter			(Scheff et al., 2017)	
MH	mid latitude land	hydro - E-P	relative to 20C	NA	drier			(Shuman and Marsicek, 2016; Routson et al., 2019)	
MCA	Caribbean	hydro - Atlantic hurricanes	ave activity index wrt 20C	$\times 10^2 kt^2$	-1.4			(Burn and Palmer, 2015)	
LIA	Caribbean	hydro - Atlantic hurricanes	ave activity index wrt 20C	$\times 10^2 kt^2$	-9.6			(Burn and Palmer, 2015)	
MCA	N Atlantic	mode - North Atlantic Oscillation	index wrt 1900-1970	standardized	-0.019	± 2.6		(Ortega et al., 2015)	
LIA	N Atlantic	mode - North Atlantic Oscillation	index wrt 1900-1970	standardized	-0.125	± 2.7		(Ortega et al., 2015)	
LGM	Atlantic	ocean - overturning circulation	relative to 20C	NA	shallower			(Hillaire-Marcel et al., 2001)	
EH	Atlantic	ocean - overturning circulation	relative to 20C	NA	stronger			(Hillaire-Marcel et al., 2001)	
EECO	global	ocean - global mean sea level	height wrt EI	m	70	63–74		(Fischer et al., 2018)	assumes total ice loss and 7 ± 1 m for steric
MPWP	global	ocean - global mean sea level	height wrt EI	m	19	12.5-23.6		Dumitru et al., in rev.	uncertainties most likely ± 1SD
MPWP	global	ocean - global mean sea level	height wrt EI	m	6 to >30			(Dutton et al., 2015)	
LIG	global	ocean - global mean sea level	height wrt EI	m	8	4.5		Kopp email 3/27/2019	assumes Gaussian uncertainty
LIG	global	ocean - global mean sea level	height wrt EI	m	7.5	≥ ± 1.5		(Dutton et al., 2015)	papers suggest larger uncertainty e.g., (Düsterhus et al., 2016; Austermann et al., 2017)
LGM	global	ocean - global mean sea level	height wrt EI	m	-134	-132--136		(Lambeck et al., 2014)	at 20.5 ka
LGM	global	ocean - global mean sea level	height wrt EI	m	-130	± 5		Kopp email 3/27/2019	average of Lambeck and

									Yokoyama
LGM	global	ocean - global mean sea level	height wrt EI	m	-130	-125- -130		(Nakada et al., 2015)	
LGM	global	ocean - global mean sea level	height wrt EI	m		-125- -130		(Yokoyama et al., 2018)	
LGM	local	ocean - global mean sea level	rate of change, max. SL fall	m/ kyr	14			(Yokoyama et al., 2018)	21.9-20.5 ka
LDG	global	ocean - global mean sea level	rate of change, max. SL rise	m/ kyr	11.8	± 0.2		(Lambeck et al., 2014)	regression w/ AR1 errors from 18-11 ka
LDG	global	ocean - global mean sea level	rate of change, max. SL rise	m/ kyr	13			(Peltier, 2004)	18-11 ka
LDG	global	ocean - global mean sea level	rate of change, max. SL rise	m/ kyr	9-10			(Yokoyama et al., 2018)	18-12 ka
LDG	global	ocean - global mean sea level	rate of change, max. SL rise	m/ kyr	11	± 2		Kopp email 3/27/2019	rough average of published values
LDG – MWP 1A	global	ocean - global mean sea level	rate of change, max. SL rise	m/ kyr	16.5	12-21		(Liu et al., 2015)	14.2-13.5 ka; 8.6 to 14.6 m (95% probability)
MH	global	ocean - global mean sea level	height wrt EI	m	-3	± 0.1		(Lambeck et al., 2014)	-3.2 ± 0.1 m at 6.2 ka and -2.7 ± 0.1 m at 5.8 ka; does not include thermal expansion
MH	global	ocean - global mean sea level	height wrt EI	m	-3	± 0.5		Kopp email 3/27/2019	rough average of Lambeck and Peltier
MH	global	ocean - global mean sea level	rate of change, max. SL rise	m/ kyr	1.2	± 0.1		(Lambeck et al., 2014)	
MCA	global	ocean - global mean sea level	rate of change, max. SL rise	m/ kyr	-0.4	± 0.2		(Kopp et al., 2016; Kemp et al., 2018)	Fig. 2.33; averaged over 300 years
MCA	global	ocean - global mean sea level	height wrt 1900	cm	-1	± 5		(Kopp et al., 2016; Kemp et al., 2018)	Fig. 2.32; Kopp email 3/27/2019 suggested ± 5 cm
LIA	global	ocean - global mean sea level	height wrt 1900	cm	-1	± 3		(Kopp et al., 2016; Kemp et al., 2018)	Fig. 2.32; Kopp email 3/27/2019
LIA	global	ocean - global mean sea level	rate of change, max. SL rise	m/ kyr	0	± 0.1		(Kopp et al., 2016; Kemp et al., 2018)	Fig. 2.33; averaged over 400 years
EI	global	ocean - global mean sea level	rate of change, max. SL rise	mm/ yr	0.6	± 0.2		(Kopp et al., 2016; Kemp et al., 2018)	Fig. 2.33; averaged over 50 years
EI	global	ocean - global mean sea level	height wrt 1900	m	-0.01	± 0.005		(Kopp et al., 2016; Kemp et al., 2018)	Fig. 2.32
P	global	ocean - global mean	height wrt 1900	m	0.16	± 0.4		(Dangendorf et al., 2017)	Fig. 2.32

		sea level							
P	global	ocean - global mean sea level	rate of change, SL rise	mm/ yr	2.9	± 0.3		(WCRP Global Sea Level Budget Group, 2018)	Fig. 2.32
MH	Pac 0-700 m	ocean - heat content	anomaly wrt EI	10^22 J	46	± 19		(Rosenthal et al., 2013)	
MH	Pac 0-700 m	ocean - temperature	anomaly wrt EI	°C	1.85	± 0.15		(Rosenthal et al., 2013)	
MH	Pac 0-700 m	ocean - temperature	rate of change MH to EI	°C/ decade	0.003	± 0.0002		(Rosenthal et al., 2013)	
MCA	Pac 0-700 m	ocean - heat content	800-1200 CE anomaly wrt EI	10^22 J	22	± 7		(Rosenthal et al., 2013)	
MCA	Pac 0-700 m	ocean - temperature	800-1200 CE anomaly wrt EI	°C	0.80	± 0.1		(Rosenthal et al., 2013)	
MCA	Pac 0-700 m	ocean - temperature	rate of change MCA to EI	°C/ decade	0.011	± 0.001		(Rosenthal et al., 2013)	
LIA	Pac 0-700 m	ocean - heat content	anomaly wrt 2015	10^22 J	2	± 2		(Rosenthal et al., 2013)	
EI to 2015	Pac 0-700 m	ocean - temperature	2015 anomaly wrt 1875	°C	0.22	± 0.1		(Roemmich et al., 2012)	
MPWP	sea surface	ocean - temperature, annual	anomaly wrt 10-0 ka	°C	2.3			(Martínez-Botí et al., 2015b)	
LIG	sea surface	ocean - temperature, annual	anomaly wrt 1870-1889	°C	0.5	± 0.3		(Hoffman et al., 2017)	
LIG	sea surface, N Atl	ocean - temperature, annual	anomaly wrt 1870-1889	°C	0.8	± 1.0		(Hoffman et al., 2017)	
LIG	sea surface, S Ocn	ocean - temperature, annual	anomaly wrt 1870-1889	°C	2.7	± 1.0		(Hoffman et al., 2017)	
LIG	sea surface, N Atl	ocean - temperature, summer	anomaly wrt EI	°C	1.2	± 0.7		(Capron et al., 2017)	
LIG	sea surface, S Ocn	ocean - temperature, summer	anomaly wrt EI	°C	1.6	± 0.8		(Capron et al., 2017)	
LGM	sea surface	ocean - temperature, annual	anomaly wrt 10-0 ka	°C	-2.2	± 0.4		(Martínez-Botí et al., 2015b)	
MPWP	sea surface	ocean - pH	mean	pH	8.05	± 0.05		(Sosdian et al., 2018)	Fig. 2.35
LDG	sea surface	ocean - pH	rate of change, max	pH/ 100 yr	-0.03			Foster email	change at 16.5 ka

References

Albani, S., Mahowald, N. M., Winckler, G., Anderson, R. F., Bradtmiller, L. I., Delmonte, B., et al. (2015). Twelve thousand years of dust: the Holocene global dust cycle constrained by natural archives. *Clim. Past* 11, 869–903. doi:10.5194/cp-11-869-2015.

Anagnostou, E., John, E., Babila, T. L., Pearson, P. N., Lunt, D. J., Gasson, E., et al. (2019). Early Cenozoic carbon cycle dynamics, in preparation.

Anagnostou, E., John, E. H., Edgar, K. M., Foster, G. L., Ridgwell, A., Inglis, G. N., et al. (2016). Changing atmospheric CO2 concentration was the primary driver of early Cenozoic climate. *Nature*. doi:10.1038/nature17423.

Austermann, J., Mitrovica, J. X., Huybers, P., and Rovere, A. (2017). Detection of a dynamic topography signal in last interglacial sea-level records. *Sci. Adv.* 3. doi:10.1126/sciadv.1700457.

Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T. F., Fischer, H., et al. (2015). Revision of the EPICA Dome C CO2 record from 800 to 600-kyr before present. *Geophys. Res. Lett.* doi:10.1002/2014GL061957.

Binney, H. A., Willis, K. J., Edwards, M. E., Bhagwat, S. A., Anderson, P. M., Andreev, A. A., et al. (2009). The distribution of late-Quaternary woody taxa in northern Eurasia: evidence from a new macrofossil database. *Quat. Sci. Rev.* doi:10.1016/j.quascirev.2009.04.016.

Binney, H., Edwards, M., Macias-Fauria, M., Lozhkin, A., Anderson, P., Kaplan, J. O., et al. (2017). Vegetation of Eurasia from the last glacial maximum to present: Key biogeographic patterns. *Quat. Sci. Rev.* doi:10.1016/j.quascirev.2016.11.022.

Burn, M. J., and Palmer, S. E. (2015). Atlantic hurricane activity during the last millennium. *Sci. Rep.* 5, 12838. Available at: https://doi.org/10.1038/srep12838.

Caballero, R., and Huber, M. (2013). State-dependent climate sensitivity in past warm climates and its implications for future climate projections. *Proc. Natl. Acad. Sci. U. S. A.* 110, 14162–7. doi:10.1073/pnas.1303365110.

Capron, E., Govin, A., Feng, R., Otto-Bliesner, B. L., and Wolff, E. W. (2017). Critical evaluation of climate syntheses to benchmark CMIP6/PMIP4 127 ka Last Interglacial simulations in the high-latitude regions. *Quat. Sci. Rev.* 168, 137–150. doi:10.1016/J.QUASCIREV.2017.04.019.

Chevalier, M., Brewer, S., and Chase, B. M. (2017). Qualitative assessment of PMIP3 rainfall simulations across the eastern African monsoon domains during the mid-Holocene and the Last Glacial Maximum. *Quat. Sci. Rev.* 156, 107–120. doi:https://doi.org/10.1016/j.quascirev.2016.11.028.

Dangendorf, S., Hay, C. C., Calafat, F. M., Marcos, M., Berk, K., and Jensen, J. Persistent acceleration in global sea-level rise since the 1970s.

de la Vega, E., Chalk, T. B., Hain, M. P., Wilson, P. A., and Foster, G. L. Multi-site Late Pleistocene high resolution CO2 record using boron isotopes and constraints on CO2 climate forcing, in preparation.

Düsterhus, A., Tamisiea, M. E., and Jevrejeva, S. (2016). Estimating the sea level highstand during the last interglacial: a probabilistic massive ensemble approach. *Geophys. J. Int.* 206, 900–920. doi:10.1093/gji/ggw174.

Dutton, A., Carlson, A. E., Long, A. J., Milne, G. A., Clark, P. U., DeConto, R., et al. (2015). Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science (80-.).* 349. doi:10.1126/science.aaa4019.

Fischer, H., Meissner, K. J., Mix, A. C., Abram, N. J., Austermann, J., Brovkin, V., et al. (2018). Palaeoclimate constraints on the impact of 2 °C anthropogenic warming and beyond. *Nat. Geosci.* 11, 474–485. doi:10.1038/s41561-018-0146-0.

Flückiger, J., Blunier, T., Stauffer, B., Chappellaz, J., Spahni, R., Kawamura, K., et al. (2004). N2O and CH4 variations during the last glacial epoch: Insight into global processes. *Global Biogeochem. Cycles* 18. doi:10.1029/2003GB002122.

Fornace, K. L., Whitney, B. S., Galy, V., Hughen, K. A., and Mayle, F. E. (2016). Late Quaternary environmental change in the interior South American tropics: new insight from leaf wax stable isotopes. *Earth Planet. Sci. Lett.* 438, 75–85. doi:https://doi.org/10.1016/j.epsl.2016.01.007.

Gingerich, P. D. Temporal Scaling of Carbon Emission and Accumulation Rates: Modern Anthropogenic Emissions Compared to Estimates of PETM-Onset Accumulation. *Paleoceanogr. Paleoclimatology* 0. doi:10.1029/2018PA003379.

Gutjahr, M., Ridgwell, A., Sexton, P. F., Anagnostou, E., Pearson, P. N., Pälike, H., et al. (2017). Very large release of mostly volcanic carbon during the Palaeocene-Eocene Thermal Maximum. *Nature* 548, 573–577. doi:10.1038/nature23646.

Harrison, S. P., Bartlein, P. J., Izumi, K., Li, G., Annan, J., Hargreaves, J., et al. (2015). Evaluation of CMIP5 palaeo-simulations to improve climate projections. *Nat. Clim. Chang.* 5, 735. Available at: http://dx.doi.org/10.1038/nclimate2649.

Hayes, C. T., McGee, D., Mukhopadhyay, S., Boyle, E. A., and Maloof, A. C. (2017). Helium and thorium isotope constraints on African dust transport to the Bahamas over recent millennia. *Earth Planet. Sci. Lett.* 457, 385–394. doi:https://doi.org/10.1016/j.epsl.2016.10.031.

Haywood, A. M., Dowsett, H. J., and Dolan, A. M. (2016). Integrating geological archives and climate models for the mid-Pliocene warm period. *Nat. Commun.* 7, 10646. Available at: https://doi.org/10.1038/ncomms10646.

Hillaire-Marcel, C., de Vernal, A., Bilodeau, G., and Weaver, A. J. (2001). Absence of deep-water formation in the Labrador Sea during the last interglacial period. *Nature* 410, 1073–1077. doi:10.1038/35074059.

Hoffman, J. S., Clark, P. U., Parnell, A. C., and He, F. (2017). Regional and global sea-surface temperatures during the last interglaciation. *Science (80-.).* 355, 276 LP-279. Available at: http://science.sciencemag.org/content/355/6322/276.abstract.

Hollis, C. J., Dunkley Jones, T., Anagnostou, E., Bijl, P. K., Cramwinckel, M. J., Cui, Y., et al. (2019). The DeepMIP contribution to PMIP4: methodologies for selection, compilation and analysis of latest Paleocene and early Eocene climate proxy data, incorporating version 0.1 of the DeepMIP database. *Geosci. Model Dev. Discuss.* 2019, 1–98. doi:10.5194/gmd-2018-309.

Jiang, D., Tian, Z., Lang, X., Kageyama, M., and Ramstein, G. (2015). The concept of global monsoon applied to the last glacial maximum: A multi-model analysis. *Quat. Sci. Rev.* 126, 126–139. doi:https://doi.org/10.1016/j.quascirev.2015.08.033.

Jungclaus, J. H., Bard, E., Baroni, M., Braconnot, P., Cao, J., Chini, L. P., et al. (2017). The PMIP4 contribution to CMIP6 – Part 3: The last millennium, scientific objective, and experimental design for the PMIP4 <i>past1000</i> simulations. *Geosci. Model Dev.* 10, 4005–4033. doi:10.5194/gmd-10-4005-2017.

Kemp, A. C., Wright, A. J., Edwards, R. J., Barnett, R. L., Brain, M. J., Kopp, R. E., et al. (2018). Relative sea-level change in Newfoundland, Canada, during the past ~3000 years. *Quat. Sci. Rev.* 201, 89–110.

Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Gehrels, W. R., et al. (2016). Temperature-driven global sea-level variability in the Common Era. *Proc. Natl. Acad. Sci.* 113, E1434–E1441. doi:10.1073/pnas.1517056113.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., and Sambridge, M. (2014). Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proc. Natl. Acad. Sci.* 111, 15296–15303. doi:10.1073/pnas.1411762111.

Liu, J., Milne, G. A., Kopp, R. E., Clark, P. U., and Shennan, I. (2015). Sea-level constraints on the amplitude and source distribution of Meltwater Pulse 1A. *Nat. Geosci.* 9, 130. Available at: https://doi.org/10.1038/ngeo2616.

Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B., et al. (2008). Orbital and millennial-scale features of atmospheric CH4 over the past 800,000 years. *Nature* 453, 383.

Lovejoy, S., Schertzer, D., and Varon, D. (2013). Do GCMs predict the climate ... or macroweather? *Earth Syst. Dyn.* 4, 439–454. doi:10.5194/esd-4-439-2013.

Marcott, S. A., Bauska, T. K., Buizert, C., Steig, E. J., Rosen, J. L., Cuffey, K. M., et al. (2014). Centennial-scale changes in the global carbon cycle during the last deglaciation. *Nature* 514, 616–619. doi:10.1038/nature13799.

Marcott, S. A., Shakun, J. D., Clark, P. U., and Mix, A. C. (2013). A Reconstruction of Regional and Global Temperature for the Past 11,300 Years. *Science (80-.).* 339, 1198 LP-1201. Available at: http://science.sciencemag.org/content/339/6124/1198.abstract.

Marquer, L., Gaillard, M. J., Sugita, S., Poska, A., Trondman, A. K., Mazier, F., et al. (2017). Quantifying the effects of land use and climate on Holocene vegetation in Europe. *Quat. Sci. Rev.* doi:10.1016/j.quascirev.2017.07.001.

Marsicek, J., Shuman, B. N., Bartlein, P. J., Shafer, S. L., and Brewer, S. (2018). Reconciling divergent trends and millennial variations in Holocene temperatures. *Nature* 554, 92. Available at: http://dx.doi.org/10.1038/nature25464.

Martínez-Botí, M. A., Foster, G. L., Chalk, T. B., Rohling, E. J., Sexton, P. F., Lunt, D. J., et al. (2015a). Plio-Pleistocene climate sensitivity evaluated using high-resolution CO2 records. *Nature* 518, 49. Available at: http://dx.doi.org/10.1038/nature14145.

Martínez-Botí, M. A., Foster, G. L., Chalk, T. B., Rohling, E. J., Sexton, P. F., Lunt, D. J., et al. (2015b). Plio-Pleistocene climate sensitivity evaluated using high-resolution CO2 records. *Nature* 518, 49–54. doi:10.1038/nature14145.

Matthes, K., Funke, B., Andersson, M. E., Barnard, L., Beer, J., Charbonneau, P., et al. (2017). Solar forcing for CMIP6 (v3.2). *Geosci. Model Dev.* 10, 2247–2302. doi:10.5194/gmd-10-2247-2017.

McGee, D., deMenocal, P. B., Winckler, G., Stuut, J. B. W., and Bradtmiller, L. I. (2013). The magnitude, timing and abruptness of changes in North African dust deposition over the last 20,000yr. *Earth Planet. Sci. Lett.* 371–372, 163–176. doi:https://doi.org/10.1016/j.epsl.2013.03.054.

Meinshausen, M., Vogel, E., Nauels, A., Lorbacher, K., Meinshausen, N., Etheridge, D. M., et al. (2017). Historical greenhouse gas concentrations for climate modelling (CMIP6). *Geosci. Model Dev.* 10, 2057–2116. doi:10.5194/gmd-10-2057-2017.

Middleton, J. L., Mukhopadhyay, S., Langmuir, C. H., McManus, J. F., and Huybers, P. J. (2018). Millennial-scale variations in dustiness recorded in Mid-Atlantic sediments from 0 to 70 ka. *Earth Planet. Sci. Lett.* 482, 12–22. doi:https://doi.org/10.1016/j.epsl.2017.10.034.

Mitchell, L., Brook, E., Lee, J. E., Buizert, C., and Sowers, T. (2013). Constraints on the late Holocene anthropogenic contribution to the atmospheric methane budget. *Science (80-.).* doi:10.1126/science.1238920.

Mitchell, L. E., Brook, E. J., Sowers, T., McConnell, J. R., and Taylor, K. (2011). Multidecadal variability of atmospheric methane, 1000–1800 C.E. *J. Geophys. Res.* 116, G02007. doi:10.1029/2010JG001441.

Nakada, M., Okuno, J., and Yokoyama, Y. (2015). Total meltwater volume since the Last Glacial Maximum and viscosity structure of Earth's mantle inferred from relative sea level changes at Barbados and Bonaparte Gulf and GIA-induced $\dot{J}2$. *Geophys. J. Int.* 204, 1237–1253. doi:10.1093/gji/ggv520.

Novello, V. F., Cruz, F. W., Vuille, M., Stríkis, N. M., Edwards, R. L., Cheng, H., et al. (2017). A high-resolution history of the South American Monsoon from Last Glacial Maximum to the Holocene. *Sci. Rep.* 7, 44267. Available at: https://doi.org/10.1038/srep44267.

Ortega, P., Lehner, F., Swingedouw, D., Masson-delmotte, V., Raible, C. C., Casado, M., et al. (2015). A model-tested North Atlantic Oscillation reconstruction for the past millennium. *Nature* 523, 71–74. doi:10.1038/nature14518.

PAGES 2k Consortium (Neukom, R., Barboza, L.A., Erb, M.P., Shi, F., Emile-Geay, J., Evans, M.N., Franke, J., Kaufman, D.S., Lücke, L., Rehfeld, K., Schurer, A., Zhu, F., Brönnimann, S., Hakim, G.J., Henley, B., Ljungqvist, F.C., McKay, Valler, V., von Gun, L. Global multi-decadal temperature variability over the Common Era. *Nat. Geosci.*

Peltier, W. R. (2004). GLOBAL GLACIAL ISOSTASY AND THE SURFACE OF THE ICE-AGE EARTH: The ICE-5G (VM2) Model and GRACE. *Annu. Rev. Earth Planet. Sci.* 32, 111–149. doi:10.1146/annurev.earth.32.082503.144359.

Pound, M. J., Tindall, J., Pickering, S. J., Haywood, A. M., Dowsett, H. J., and Salzmann, U. (2014). Late Pliocene lakes and soils: a global data set for the analysis of climate feedbacks in a warmer world. *Clim. Past* 10, 167–180. doi:10.5194/cp-10-167-2014.

Rehfeld, K., Münch, T., Ho, S. L., and Laepple, T. (2018). Global patterns of declining temperature variability from the Last Glacial Maximum to the Holocene. *Nature* 554, 356. Available at: http://dx.doi.org/10.1038/nature25454.

Rhodes, R. H., Brook, E. J., Chiang, J. C. H., Blunier, T., Maselli, O. J., McConnell, J. R., et al. (2015). Enhanced tropical methane production in response to iceberg discharge in the North Atlantic. *Science (80-.).* doi:10.1126/science.1262005.

Rhodes, R. H., Faïn, X., Stowasser, C., Blunier, T., Chappellaz, J., McConnell, J. R., et al. (2013). Continuous methane measurements from a late Holocene Greenland ice core: Atmospheric and in-situ signals. *Earth Planet. Sci. Lett.* doi:10.1016/j.epsl.2013.02.034.

Roemmich, D., John Gould, W., and Gilson, J. (2012). 135 years of global ocean warming between the Challenger expedition and the Argo Programme. *Nat. Clim. Chang.* 2, 425. Available at: https://doi.org/10.1038/nclimate1461.

Rosenthal, Y., Linsley, B. K., and Oppo, D. W. (2013). Pacific Ocean Heat Content During the Past 10,000 Years. *Science (80-.).* 342, 617–621. doi:10.1126/science.1240837.

Routson, C., Mckay, N., Kaufman, D., Erb, M. P., Goosse, H., Rodysill, J., et al. (2019). Mid-latitude net precipitation decreased with Arctic warming during the Holocene. *Nature*, in press.

Salzmann, U., Haywood, A. M., Lunt, D. J., Valdes, P. J., and Hill, D. J. (2008). A new global biome reconstruction and data-model comparison for the Middle Pliocene. *Glob. Ecol. Biogeogr.* doi:10.1111/j.1466-8238.2008.00381.x.

Scheff, J., Seager, R., and Liu, H. (2017). Are Glacials Dry ? Consequences for Paleoclimatology and for Greenhouse Warming. *J. Clim.* 30, 6593–6609. doi:10.1175/JCLI-D-16-0854.1.

Schilt, A., Baumgartner, M., Blunier, T., Schwander, J., Spahni, R., Fischer, H., et al. (2010). Glacial–interglacial and millennial-scale variations in the atmospheric nitrous oxide concentration during the last 800,000 years. *Quat. Sci. Rev.* 29, 182–192. doi:https://doi.org/10.1016/j.quascirev.2009.03.011.

Schilt, A., Brook, E. J., Bauska, T. K., Baggenstos, D., Fischer, H., Joos, F., et al. (2014). Isotopic constraints on marine and terrestrial N2O emissions during the last deglaciation. *Nature* 516, 234. Available at: https://doi.org/10.1038/nature13971.

Seddon, A. W. R., Macias-Fauria, M., and Willis, K. J. (2015). Climate and abrupt vegetation change in Northern Europe since the last deglaciation. *Holocene*. doi:10.1177/0959683614556383.

Shuman, B. (2012). Patterns, processes, and impacts of abrupt climate change in a warm world: the past 11,700 years. *Wiley Interdiscip. Rev. Clim. Chang.* 3, 19–43. doi:10.1002/wcc.152.

Shuman, B. N., and Marsicek, J. (2016). The structure of Holocene climate change in mid-latitude North America. *Quat. Sci. Rev.* 141, 38–51. doi:10.1016/j.quascirev.2016.03.009.

Snyder, C. W. (2016). Evolution of global temperature over the past two million years. *Nature* 538, 226. Available at: http://dx.doi.org/10.1038/nature19798.

Solomina, O. N., Bradley, R. S., Hodgson, D. A., Ivy-Ochs, S., Jomelli, V., Mackintosh, A. N., et al. (2015). Holocene glacier fluctuations. *Quat. Sci. Rev.* doi:10.1016/j.quascirev.2014.11.018.

Sosdian, S. M., Rosenthal, Y., and Toggweiler, J. R. (2018). Deep Atlantic Carbonate Ion and CaCO3 Compensation During the Ice Ages. *Paleoceanogr. Paleoclimatology* 33, 546–562. doi:10.1029/2017PA003312.

Toohey, M., and Sigl, M. (2017). Volcanic stratospheric sulfur injections and aerosol optical depth from 500 BCE to 1900 CE. *Earth Syst. Sci. Data* 9, 809–831. doi:10.5194/essd-9-809-2017.

WAIS Divide Project Members., Members, W. D. P., Buizert, C., Adrian, B., Ahn, J., Albert, M., et al. (2015). Precise interpolar phasing of abrupt climate change during the last ice age. *Nature* 520, 661. Available at:

https://doi.org/10.1038/nature14401.
WCRP Global Sea Level Budget Group (2018). Global sea-level budget 1993–present. *Earth Syst. Sci. Data* 10, 1551–1590. doi:10.5194/essd-10-1551-2018.
Williams, J. W., Shuman, B. N., Webb, T., Bartlein, P. J., and Leduc, P. L. (2004). Late-Quaternary vegetation dynamics in north America: Scaling from taxa to biomes. *Ecol. Monogr.* doi:10.1890/02-4045.
Williams, J. W., Tarasov, P., Brewer, S., and Notaro, M. (2011). Late Quaternary variations in tree cover at the northern forest-tundra ecotone. *J. Geophys. Res. Biogeosciences*. doi:10.1029/2010JG001458.
Williams, R. H., McGee, D., Kinsley, C. W., Ridley, D. A., Hu, S., Fedorov, A., et al. (2016). Glacial to Holocene changes in trans-Atlantic Saharan dust transport and dust-climate feedbacks. *Sci. Adv.* 2, e1600445. doi:10.1126/sciadv.1600445.
Wu, C. J., Usoskin, I. G., Krivova, N., Kovaltsov, G. A., Baroni, M., Bard, E., et al. (2018). Solar activity over nine millennia: A consistent multi-proxy reconstruction. *A&A* 615, A93. doi:10.1051/0004-6361/201731892.
Yokoyama, Y., Esat, T. M., Thompson, W. G., Thomas, A. L., Webster, J. M., Miyairi, Y., et al. (2018). Rapid glaciation and a two-step sea level plunge into the Last Glacial Maximum. *Nature* 559, 603–607. doi:10.1038/s41586-018-0335-4.