Implications of recent multimodel attribution studies for climate sensitivity – Supplemental Material

Nicholas Lewis
Bath, United Kingdom

1. AMO influence on scaling factors

Data used: annual forcing and AMO time series

GHG is the sum of CO2 and GHG Other ERF in Table AII 1.2 of AR5; natural (NAT) is the sum of Solar and scaled* Volcano ERF in that table; and other anthropogenic (OTH) is the sum of ERF for all other forcing agents in Table AII 1.2 of AR5
The AMO time series is 'AMO unsmooth long' downloaded from http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data on 15Apr14.
See http://www.esrl.noaa.gov/psd/data/timeseries/AMO/ for details

* Volcanic forcing is scaled down to 55% of AR5 level: for reason see Lewis and Curry (2014) Clim Dyn DOI 10.1007/s00382-014-2342-y

Year	AR5 Table AII.1.2 ERF estimates			AMO
	GHG	Other Anth	Natural*	index
1856	0.210	-0.160	-0.573	0.197
1857	0.210	-0.160	-0.862	-0.022
1858	0.210	-0.160	-0.419	0.005
1859	0.211	-0.162	-0.158	0.016
1860	0.212	-0.163	-0.040	0.083
1861	0.213	-0.164	-0.005	0.180
1862	0.214	-0.164	-0.180	-0.200
1863	0.216	-0.165	-0.132	-0.117
1864	0.219	-0.167	-0.086	0.060
1865	0.222	-0.166	-0.046	0.166
1866	0.228	-0.166	-0.035	0.201
1867	0.234	-0.168	-0.037	0.140
1868	0.241	-0.168	-0.039	0.153
1869	0.250	-0.170	-0.019	0.094
1870	0.259	-0.171	-0.042	0.017
1871	0.268	-0.172	0.011	0.030
1872	0.277	-0.172	-0.002	0.092
1873	0.285	-0.173	-0.026	0.047
1874	0.291	-0.173	-0.028	-0.022
1875	0.296	-0.174	-0.029	0.034
1876	0.301	-0.175	-0.112	-0.023
1877	0.303	-0.176	-0.102	0.240
1878	0.305	-0.178	-0.082	0.451
1879	0.309	-0.178	-0.072	0.124
1880	0.311	-0.178	-0.053	0.061
1881	0.315	-0.180	-0.021	0.041
1882	0.320	-0.179	-0.033	-0.027
1883	0.326	-0.181	-0.677	-0.034
1884	0.334	-0.182	-1.948	-0.077
1885	0.342	-0.184	-0.864	-0.026
1886	0.350	-0.183	-0.509	0.121
1887	0.360	-0.184	-0.542	0.120
1888	0.370	-0.186	-0.340	0.193
1889	0.380	-0.186	-0.440	0.196
1890	0.390	-0.187	-0.577	-0.146
1891	0.401	-0.188	-0.433	0.033
1892	0.411	-0.190	-0.299	-0.093
1893	0.421	-0.189	-0.089	-0.007
1894	0.430	-0.190	0.017	-0.245
1895	0.436	-0.191	0.038	-0.096
1896	0.442	-0.193	-0.225	0.105
1897	0.447	-0.194	-0.237	0.108
1898	0.450	-0.194	-0.177	0.073
1899	0.452	-0.195	-0.086	0.126
1900	0.456	-0.196	-0.056	0.096
1901	0.461	-0.198	-0.057	0.087
1902	0.467	-0.197	-0.323	-0.103
1903	0.476	-0.199	-1.026	-0.194
1904	0.485	-0.199	-0.429	-0.348
1905	0.496	-0.199	-0.195	-0.203
1906	0.507	-0.201	-0.068	-0.074
1907	0.517	-0.202	-0.125	-0.227
1908	0.528	-0.202	-0.118	-0.130
1909	0.537	-0.204	-0.057	-0.137
1910	0.546	-0.204	-0.047	-0.247
1911	0.555	-0.205	-0.060	-0.213
1912	0.565	-0.205	-0.306	-0.227
1913	0.575	-0.204	-0.372	-0.387
1914	0.586	-0.205	-0.171	-0.289
1915	0.598	-0.205	-0.042	0.095
1916	0.611	-0.205	0.027	-0.075
1917	0.625	-0.205	0.059	-0.278
1918	0.638	-0.206	0.094	-0.259
1919	0.649	-0.207	0.046	-0.185
1920	0.659	-0.205	-0.085	-0.334
1921	0.668	-0.208	-0.098	-0.219
1922	0.675	-0.212	-0.054	-0.318
1923	0.682	-0.214	-0.039	-0.322
1924	0.689	-0.217	-0.070	-0.150

1925	0.696	-0.220	-0.056	-0.157
1926	0.704	-0.224	-0.008	0.088
1927	0.713	-0.226	0.036	0.113
1928	0.724	-0.228	-0.036	-0.003
1929	0.735	-0.231	-0.110	-0.109
1930	0.745	-0.235	-0.035	0.014
1931	0.756	-0.236	-0.060	0.182
1932	0.766	-0.235	-0.126	0.232
1933	0.776	-0.234	-0.125	0.196
1934	0.785	-0.234	-0.082	-0.004
1935	0.796	-0.234	-0.063	0.022
1936	0.807	-0.233	0.027	0.154
1937	0.817	-0.233	0.048	0.297
1938	0.828	-0.233	0.011	0.245
1939	0.838	-0.234	0.039	0.113
1940	0.847	-0.234	0.029	-0.026
1941	0.856	-0.236	0.030	0.177
1942	0.862	-0.238	-0.025	0.187
1943	0.866	-0.240	-0.060	0.036
1944	0.869	-0.242	-0.039	0.352
1945	0.872	-0.244	-0.009	0.223
1946	0.875	-0.247	-0.003	0.022
1947	0.877	-0.249	0.066	-0.083
1948	0.881	-0.250	0.119	0.015
1949	0.888	-0.253	0.082	0.094
1950	0.895	-0.254	0.069	-0.007
1951	0.904	-0.266	0.009	0.205
1952	0.917	-0.276	-0.010	0.297
1953	0.931	-0.286	-0.016	0.266
1954	0.946	-0.297	-0.052	0.045
1955	0.964	-0.308	-0.013	0.194
1956	0.983	-0.318	0.050	-0.018
1957	1.003	-0.328	0.115	0.042
1958	1.022	-0.338	0.194	0.216
1959	1.043	-0.349	0.159	0.055
1960	1.064	-0.361	0.082	0.237
1961	1.083	-0.374	-0.041	0.101
1962	1.102	-0.388	-0.128	0.074
1963	1.119	-0.401	-0.595	0.006
1964	1.137	-0.415	-0.971	-0.094
1965	1.160	-0.427	-0.583	-0.158
1966	1.186	-0.440	-0.304	0.006
1967	1.215	-0.453	-0.151	-0.096
1968	1.245	-0.465	-0.285	-0.165
1969	1.277	-0.478	-0.391	0.011
1970	1.311	-0.491	-0.142	-0.102
1971	1.346	-0.491	-0.001	-0.311
1972	1.384	-0.488	0.021	-0.353
1973	1.423	-0.485	-0.066	-0.215
1974	1.462	-0.483	-0.156	-0.420
1975	1.498	-0.481	-0.407	-0.298
1976	1.536	-0.478	-0.196	-0.363
1977	1.577	-0.476	-0.029	-0.189
1978	1.623	-0.473	0.019	-0.179
1979	1.674	-0.469	0.043	-0.110
1980	1.721	-0.468	0.081	-0.018
1981	1.762	-0.476	0.078	-0.075
1982	1.802	-0.486	-0.635	-0.211
1983	1.847	-0.497	-0.940	-0.069
1984	1.893	-0.506	-0.397	-0.206
1985	1.934	-0.513	-0.168	-0.265
1986	1.975	-0.523	-0.181	-0.272
1987	2.021	-0.532	-0.123	0.069
1988	2.072	-0.540	-0.015	-0.002
1989	2.119	-0.551	0.069	-0.080
1990	2.159	-0.560	0.036	-0.035
1991	2.193	-0.566	-0.617	-0.128
1992	2.218	-0.571	-1.527	-0.215
1993	2.241	-0.575	-0.611	-0.207
1994	2.270	-0.579	-0.248	-0.173
1995	2.304	-0.582	-0.118	0.140
1996	2.334	-0.585	-0.093	-0.053
1997	2.365	-0.589	-0.053	0.057
1998	2.403	-0.591	0.021	0.377
1999	2.441	-0.592	0.077	0.123
2000	2.467	-0.595	0.100	0.034
2001	2.493	-0.591	0.087	0.125
2002	2.528	-0.588	0.081	0.071
2003	2.563	-0.583	0.001	0.237
2004	2.597	-0.573	-0.016	0.213
2005	2.630	-0.568	-0.052	0.299
2006	2.665	-0.563	-0.071	0.274
2007	2.697	-0.558	-0.072	0.155
2008	2.728	-0.549	-0.080	0.146
2009	2.761	-0.548	-0.096	0.047
2010	2.794	-0.540	-0.054	0.358
2011	2.831	-0.537	-0.039	0.111

A: Case with AMO peak-to-trough influence on GMST of 0.12 K, showing that biases the GHG, OTH and NAT scaling factors substantially

Prepared decadal data

Total forcing is the sum of GHG,other anthropogenic (OTH) & natural (NAT) forcings
Forced response= decadal-mean Total forcing x 0.36 K/Wm-2 assumed response
Scaled AMO is the decadal-mean AMO index multiplied by a factor of 0.2741,
that being the ratio producing a 0.12 K range in the Scaled AMO.

AMO influence on GMST	
scaled by:	0.2741
Unscaled AMO range	Scaled AMO range
0.438	0.120

With AMO scaled to peak-to trough influence of: **0.12 K**

Assumed 'true' response of GMST to total forcing 0.36 K/Wm-2

Decade ending	Decadal mean AR5 ERF estimates GHG	OTH	NAT	Total forcing	Forced response	Unscaled AMO	Scaled AMO	**Synthetic GMST:** Forced response + scaled AMO
1870	0.230	-0.167	-0.062	0.001	0.000	0.069	0.019	0.019
1880	0.295	-0.175	-0.049	0.070	0.025	0.103	0.028	0.054
1890	0.349	-0.183	-0.595	-0.430	-0.155	0.036	0.010	-0.145
1900	0.435	-0.192	-0.154	0.088	0.032	0.010	0.003	0.034
1910	0.502	-0.201	-0.244	0.057	0.021	-0.158	-0.043	-0.023
1920	0.606	-0.205	-0.081	0.320	0.115	-0.215	-0.059	0.056
1930	0.703	-0.222	-0.047	0.435	0.156	-0.106	-0.029	0.127
1940	0.802	-0.234	-0.030	0.537	0.193	0.141	0.039	0.232
1950	0.874	-0.245	0.023	0.652	0.235	0.102	0.028	0.262
1960	0.978	-0.313	0.052	0.717	0.258	0.154	0.042	0.300
1970	1.184	-0.433	-0.359	0.391	0.141	-0.042	-0.011	0.129
1980	1.524	-0.479	-0.069	0.976	0.351	-0.245	-0.067	0.284
1990	1.958	-0.518	-0.228	1.213	0.437	-0.115	-0.031	0.405
2000	2.324	-0.583	-0.307	1.434	0.516	-0.005	-0.001	0.515
2010	2.646	-0.566	-0.027	2.052	0.739	0.192	0.053	0.792

Decadal regressions of Synthetic GMST on GHG, Other Anthropogenic and Natural forcings

Since forcings rather than (as is usual in detection and attribution analyses) the responses thereto are used as the regressors, the scaling factors for each forcing are obtained by dividing their regression coefficient by the true GMST response to forcing of 0.36 K/Mm-2.

Over 1951-2010 period

Trend in scaled AMO (K/decade)	0.0034
Trend in forced response (K/decade)	0.1033
Increase in synthetic GMST trend due to AMO	**3.3%**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.998
R Square	0.996
Adjusted R Square	0.990
Standard Error	0.023
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.262	0.087	165.142	0.006
Residual	2	0.001	0.001		
Total	5	0.263			

		Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*	Scaling factor
	Intercept	0.317	0.096	3.306	0.081	-0.096	0.730	-0.096	0.730	
GHG	X Variable 1	0.587	0.060	9.785	0.010	0.329	0.845	0.329	0.845	**1.63**
OTH	X Variable 2	1.915	0.427	4.482	0.046	0.077	3.753	0.077	3.753	**5.32**
NAT	X Variable 3	0.181	0.101	1.786	0.216	-0.255	0.618	-0.255	0.618	**0.50**

Over 1901-2010 period

Trend in scaled AMO (K/decade)	0.0041
Trend in forced response (K/decade)	0.0569
Increase in synthetic GMST trend due to AMO	**7.2%**

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.989
R Square	0.977
Adjusted R Square	0.968
Standard Error	0.041
Observations	11

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.511	0.170	101.060	0.000
Residual	7	0.012	0.002		
Total	10	0.523			

		Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*	Scaling factor
	Intercept	0.008	0.042	0.199	0.848	-0.091	0.107	-0.091	0.107	
GHG	X Variable 1	0.434	0.068	6.377	0.000	0.273	0.595	0.273	0.595	**1.21**
OTH	X Variable 2	0.635	0.342	1.853	0.106	-0.175	1.444	-0.175	1.444	**1.76**
NAT	X Variable 3	0.451	0.117	3.841	0.006	0.173	0.728	0.173	0.728	**1.25**

A: Case with AMO peak-to-trough influence on GMST of 0.12 K, showing that biases the GHG, OTH and NAT scaling factors substantially (cont.)

Over 1861-2010 period

SUMMARY OUTPUT

Trend in scaled AMO (K/decade)	-0.0003
Trend in forced response (K/decade)	0.0467
Increase in synthetic GMST trend due to AMO	**-0.6%**

Regression Statistics	
Multiple R	0.990
R Square	0.979
Adjusted R Square	0.974
Standard Error	0.039
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.778	0.259	174.520	0.000
Residual	11	0.016	0.001		
Total	14	0.794			

		Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*	Scaling factor
	Intercept	0.040	0.034	1.173	0.265	-0.035	0.114	-0.035	0.114	
GHG	X Variable 1	0.434	0.058	7.546	0.000	0.307	0.561	0.307	0.561	**1.21**
OTH	X Variable 2	0.724	0.283	2.562	0.026	0.102	1.347	0.102	1.347	**2.01**
NAT	X Variable 3	0.378	0.065	5.847	0.000	0.235	0.520	0.235	0.520	**1.05**

B: Case with AMO peak-to-trough influence on GMST tiny at 0.001 K, showing that correct scaling factors of almost one are then obtained

Prepared decadal data

Total forcing is the sum of GHG,other anthropogenic (OTH) & natural (NAT) forcings
Forced response= decadal-mean Total forcing x 0.36 K/Wm-2 assumed response
The decadal-mean AMO index is multiplied by 0.0023, produce a tiny 0.001 K range in the Scaled AMO

AMO influence on GMST scaled by: 0.0023

With AMO scaled to peak-to trough influence of: **0.001 K**

	Assumed 'true' response of GMST to total forcing				0.36 K/Wm-2	Unscaled AMO range	Scaled AMO range	
						0.438	0.001	
Decade ending	Decadal mean AR5 ERF estimates GHG	OTH	NAT	Total forcing	Forced response	Unscaled AMO	Scaled AMO	**Synthetic GMST:** Forced response + scaled AMO
1870	0.230	-0.167	-0.062	0.001	0.000	0.069	0.0002	0.000
1880	0.295	-0.175	-0.049	0.070	0.025	0.103	0.0002	0.026
1890	0.349	-0.183	-0.595	-0.430	-0.155	0.036	0.0001	-0.155
1900	0.435	-0.192	-0.154	0.088	0.032	0.010	0.0000	0.032
1910	0.502	-0.201	-0.244	0.057	0.021	-0.158	-0.0004	0.020
1920	0.606	-0.205	-0.081	0.320	0.115	-0.215	-0.0005	0.115
1930	0.703	-0.222	-0.047	0.435	0.156	-0.106	-0.0002	0.156
1940	0.802	-0.234	-0.030	0.537	0.193	0.141	0.0003	0.194
1950	0.874	-0.245	0.023	0.652	0.235	0.102	0.0002	0.235
1960	0.978	-0.313	0.052	0.717	0.258	0.154	0.0004	0.258
1970	1.184	-0.433	-0.359	0.391	0.141	-0.042	-0.0001	0.141
1980	1.524	-0.479	-0.069	0.976	0.351	-0.245	-0.0006	0.351
1990	1.958	-0.518	-0.228	1.213	0.437	-0.115	-0.0003	0.436
2000	2.324	-0.583	-0.307	1.434	0.516	-0.005	0.0000	0.516
2010	2.646	-0.566	-0.027	2.052	0.739	0.192	0.0004	0.739

B: Case with AMO peak-to-trough influence on GMST tiny at 0.001 K, showing that correct scaling factors of almost one are then obtained (cont.)

Decadal regressions of Synthetic GMST on GHG, Other Anthropogenic and Natural forcings

Since forcings rather than (as is usual in detection and attribution analyses) the responses thereto are used as the regressors, the scaling factors for each forcing are obtained by dividing their regression coefficient by the true GMST response to forcing of 0.36 K/Mm-2.

Over 1951-2010 period

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1.000
R Square	1.000
Adjusted R Square	1.000
Standard Error	0.000
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.245	0.082	966851.58	0.000
Residual	3	0.000	0.000		
Total	6	0.245			

		Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*	Scaling factor
	Intercept	0.001	0.001	1.768	0.175	-0.001	0.003	-0.001	0.003	
GHG	X Variable 1	0.361	0.001	631.821	0.000	0.359	0.363	0.359	0.363	**1.00**
OTH	X Variable 2	0.367	0.004	104.160	0.000	0.356	0.378	0.356	0.378	**1.02**
NAT	X Variable 3	0.359	0.001	316.850	0.000	0.356	0.363	0.356	0.363	**1.00**

Over 1901-2010 period

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1.000
R Square	1.000
Adjusted R Square	1.000
Standard Error	0.000
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.495	0.165	1524610.0	0.000
Residual	8	0.000	0.000		
Total	11	0.495			

		Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*	Scaling factor
	Intercept	0.000	0.000	0.444	0.669	-0.001	0.001	-0.001	0.001	
GHG	X Variable 1	0.361	0.001	661.593	0.000	0.359	0.362	0.359	0.362	**1.00**
OTH	X Variable 2	0.363	0.003	133.105	0.000	0.356	0.369	0.356	0.369	**1.01**
NAT	X Variable 3	0.361	0.001	390.751	0.000	0.359	0.363	0.359	0.363	**1.00**

Over 1861-2010 period

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1.000
R Square	1.000
Adjusted R Square	1.000
Standard Error	0.000
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	0.743	0.248	2401442.52	2.89374E-32
Residual	11	0.000	0.000		
Total	14	0.743			

		Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*	Scaling factor
	Intercept	0.000	0.000	1.173	0.265	0.000	0.001	0.000	0.001	
GHG	X Variable 1	0.361	0.000	752.434	0.000	0.360	0.362	0.360	0.362	**1.00**
OTH	X Variable 2	0.363	0.002	154.087	0.000	0.358	0.368	0.358	0.368	**1.01**
NAT	X Variable 3	0.360	0.001	669.062	0.000	0.359	0.361	0.359	0.361	**1.00**

2. Further details relating to data

Inclusion of ozone as a GHG

Per the estimates in Shindell (2014), the inclusion of ozone increased the rise in forcing over the NorESM1-M Historical GHG simulation up to 2000 by approximately 23%. In the absence of an estimate of ozone forcing in CNRM-CM5, it is assumed to have increased the change in forcing for that model over the Historical GHG simulation by 12%, based on the estimates in Table AII.1.2 of AR5. Since the evolution of total ozone forcing is almost perfectly correlated with that of well-mixed greenhouse gases, the inclusion of ozone in the CNRM-CM5 and NorESM1-M Historical GHG simulations, representing two models out of eight (in J13) or nine (in G13), is allowed for by adjusting up the AR5 Table AII 1.2 time series for GHG ERF used to force the EBM. The adjustment made is 4% (the sum of 12% and 23%, divided by the average of 8 and 9) for all years.

Estimation of a PDF for effective heat capacity $C_{\mathrm{H}}^{\mathrm{t}}$

A PDF for $C_{\mathrm{H}}^{\mathrm{t}}$ is estimated by calculating the quotients of many pairs of random samples taken from the error distributions for ΔHC and ΔT_{G}, which are assumed to be independent, and computing the sample histogram of the quotients. In essence, this is the method used by Gregory et al. (2002) directly to compute a PDF for S from the error distributions for the relevant observables. In Bayesian terms, the method uses uniform prior distributions for ΔHC and ΔT_{G}. Since errors in the estimates of ΔHC and ΔT_{G} are taken to have Gaussian distributions, uniform priors are completely noninformative and their use results in objective estimated posterior distributions for ΔHC and ΔT_{G} (Datta and Sweeting 2005). The sampling-based method then provides a correctly calculated, objective Bayesian, estimated posterior density for $C_{\mathrm{H}}^{\mathrm{t}}$, that is $p_{C_{\mathrm{H}}^{t}}(C_{\mathrm{H}}^{t} \mid \Delta HC, \Delta T_{G})$. A profile likelihood for C_{H} is also computed, by, at each C_{H} value, taking the maximum, across all ΔHC and ΔT_{G} combinations whose quotient equals that C_{H} value, of the product of the likelihood functions for ΔHC and ΔT_{G} (which their error distributions provide).

Additional references

Datta, G.S. and T.J. Sweeting, 2005: Probability Matching Priors. *Handbook of Statistics 25*.Dey, D.K. and C. R. Rao, Elsevier, 1062pp.

Gregory J, Stouffer RJ, Raper SCB, Stott PA, Rayner NA (2002) An Observationally Based Estimate of the Climate Sensitivity. *J. Climate*, 15, 3117–3121.