Effect of Missing Data on Estimates of Near-Surface Temperature Change Since 1900

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Abstract

The apparent warming of Earth's surface during the 20th century may be biased by large changes in the coverage of surface temperature measurements since 1900. We investigate this issue using climate model simulations. By imposing observed coverage changes on simulated surface temperatures, we obtain estimates of 20th-century temperature-change for both full global coverage and for actual historical coverage. In 10 of 16 simulations including human climate perturbations, the temperature change from globally complete model output is significantly larger than that derived from historically-masked model output. The remaining 6 simulations show no significant difference between complete and masked model output. Thus, our results do not support the hypothesis that the increase in Earth's surface temperature has been overestimated due to incomplete observational data. Rather, if the simulations we analyzed are realistic, the true temperature increase over the last century is slightly larger than that estimated from available observations. We also analyzed 8 simulations of natural internal climate variability which omit human climate perturbations. In none of these simulations does the temperature change during 100 years—whether obtained from globally complete or masked model output—come close to the observed 20th century temperature increase.

Introduction

The increase in near-surface air temperature (SAT) since 1900 has been estimated from observations that do not completely cover the Earth's surface. The fraction of the surface that is sampled has changed markedly over the past 140 years (Jones, 1994; Jones *et al.*, 1999; Parker *et al.*, 1994; Nicholls *et al.*, 1996), from roughly 17% in 1860 to 40% in 1900, reaching a maximum of 87% in 1987. These two factors–incomplete measurement coverage, and large, non-random changes in measurement coverage with time–introduce uncertainties in estimates of global-scale SAT changes. Singer (1999) has argued that these effects markedly bias the estimated global-mean trend of ca. 0.6°C over the past century.

Several attempts have been made to quantify the effects of incomplete, time-varying coverage on the apparent temperature trend. "Frozen grid" methods analyze a limited subset of grid-points that are continuously available over some stipulated period (Jones *et al.*, 1986a,b). Such results are then compared to those from grids with time-varying coverage. This allows estimation of the effects of coverage changes, but does not allow estimation of errors introduced by neglecting to sample certain geographical regions. Other methods for estimating sampling errors include optimal averaging techniques (Smith *et al.*, 1994), or methods that attempt to assess correlation length scales, i.e., the effective spatial representativeness of measurements in individual grid-boxes (Jones *et al.* 1997).

Another approach is to estimate near-surface temperature sampling errors using the globally-complete output from climate models. Such work has focussed mainly on climate model control integrations, which simulate internal climate variability only (omitting changes in greenhouse gases, anthropogenic aerosols, solar variability, volcanic dust, and other forcings). These integrations have been used to verify empirical estimates of correlation length scales and spatial degrees of freedom (Jones *et al.*, 1997; Madden *et al.*, 1993). Karl *et al.* (1994) used a climate model simulation of increasing atmospheric CO_2 to assess the impact of incomplete and time-varying measurement coverage on century timescale estimates of surface temperature change. Karl *et al.* estimated that the sampling error was an order of magnitude smaller than the observed change of roughly 0.6°C since 1900.

Here, we extend the Karl *et al*. analysis to 24 simulations performed with coupled atmosphere-ocean General Circulation Models (GCMs; Table 1). Sixteen of these simulations include effects of estimated historical changes in both greenhouse gases and anthropogenic sulfate aerosols. Forcing changes due to volcanoes and solar luminosity variations are not represented. The remaining 8 are unforced "control" simulations. We analyzed both types of simulations to investigate whether sampling errors are markedly different in forced and unforced experiments. The use of multiple models, driven by similar forcing histories, provides information on how sampling errors depend on uncertainties in the specified climate forcing, the model-predicted climate response, and simulated natural temperature variability.

Data Analysis

We obtain measurement coverage information from a dataset of sea-surface temperatures (SSTs) merged with 2m temperatures over land (Jones, 1994; Jones *et al.*, 1999; Parker *et al.*, 1994). This data set consists of observations in the form of monthly-mean anomalies (relative to climatological monthly means over 1961-1990) on a 5° by 5° latitude/longitude grid. They span the period January 1856 through December 1998. Annual-mean anomalies were calculated from the monthly-mean observed data. Simulated SATs were processed in a way analogous to the observations, yielding annual-mean anomalies. Simulated temperature anomalies were interpolated to the same 5° by 5° grid as the observations. One difference between the observed and simulated temperatures is that the number of observations within a 5° by 5° grid varies in space and time; in our analyses of simulated temperatures, we have not represented any effect this might have on global-mean temperature anomalies. From the grid-transformed model annual anomaly data we computed both 'true' spatial averages, $\langle M_t \rangle$ based on globally complete model output, and 'masked' spatial averages $\langle M_t^* \rangle$ based on the imposed observed coverage. Figure 1 shows both 'true' and 'masked' spatial averages for one specific climate-change integration.

Next, we operate on the difference time series $\langle \Delta D_t \rangle = \langle M_t^* \rangle - \langle M_t \rangle$ for each model integration. We fit least-squares linear trends $\hat{\beta}_1$ to $\langle \Delta D_t \rangle$, on timescales ranging from 30 years to the total length of each model simulation. Thus $\hat{\beta}_1$ and its estimated standard error s_e provide estimates of the difference trend (and its attendant statistical uncertainty) arising from incomplete and time-varying observational coverage. Since there is much variability common to $\langle M_t \rangle$ and $\langle M_t^* \rangle$, the difference time series $\langle \Delta D_t \rangle$ is relatively noise-free; it thus provides an accurate measure of the effects of coverage changes on the apparent temperature trend.

Results

Figure 2 shows values of $\hat{\beta}_1$ and associated 95% confidence intervals, adjusted for autocorrelation effects (as in Santer *et al.*, 2000) for climate change and control simulations. For each climate-change simulation, we derive temperature difference trends for the period 1899-1998 (except for the CCCMA simulations, which start in 1900). In addition, for simulations which start as far back as 1860, we analyze the period 1860-1998 (Table 1). For each control simulation, we analyze segment(s) having the same length as the climate change simulation performed with the same model (Table 1). If the line of zero difference trend in Figure 2 is encompassed by the adjusted 95% confidence interval, we conclude that the imposed observational coverage does not have a significant impact on the estimate of the ‘true’ trend.

Six of 16 climate-change simulations yield trend errors that are consistent with zero. These comparatively small values are in good agreement with earlier error estimates of roughly 0.05°C/100 years obtained by Karl *et al*. (1994). However, we also find that missing data leads to significant underestimates of the true global trend in 10 of the 16 climate change simulations we analyzed. None of the 16 climate change simulations show a significant overestimate of the true temperature trend.

The largest possible trend errors in the climate change simulations are +0.06 ± 0.07°C/100 years (MPI) and -0.13 ± 0.04°C/100 years (CCCMA GS3). Thus, if the simulations analyzed here provide credible estimates of human effects on historical climate, it is unlikely that missing observational data have significantly biased the observed near-surface temperature trend of ca. 0.6°C over the past century. It is possible that the true global-scale temperature change over the past century was larger than the change estimated from incomplete observations. Our analyses of data over the period 1860-1998 suggest that similar conclusions hold for this longer period.

We also investigated coverage effects on trends for the 30-year and 50-year periods ending in 1998. For both periods, only 3 of 16 perturbation simulations had significant trends in the temperature differences (masked vs. globally complete model output). It is expected that difference trends will be smaller for these analysis periods than for 1899-

1998, since coverage is greater and coverage changes are smaller in the second half of the 20th century.

For the control simulations we find that 4 of 8 simulations have temperature difference trends that are consistent with zero, and three simulations have difference trends which are significantly less than zero (meaning that the ‘true’ global-mean trend is greater than that estimated from incomplete data). The difference trend is significantly greater than zero in only one simulation. The largest possible trend errors in the control simulations are +0.14 ± 0.04°C/100 years (MPI) and -0.08 ± 0.06°C/100 years (CSM). From this small sample of control run results, there is no compelling evidence that coverage changes introduce an overall bias in century-timescale temperature trend estimates. This is in apparent contrast to results from perturbed runs. Temperature trends in the control simulations never exceed ca. +0.25°C/140 years, regardless of whether they are computed from full coverage or masked model data. This suggests that natural internal variability alone (as simulated in the models considered here) cannot fully explain the observed global-scale temperature changes over the last century. This, confirms earlier work (e.g. Wigley and Raper, 1990; Stouffer *et al.,* 1994).

In the climate change experiments, therefore, incomplete coverage leads to a larger fraction of significant trend underestimates (63%) than in the control integrations (38%). The significance of this difference is difficult to evaluate given the small sample sizes (16 and 8, respectively). One possible explanation for this result is that the significant difference trends found in most of the climate change simulations we analyzed are due to geographically varying responses to human-induced climate perturbations. Most climate models show enhanced warming at high latitudes in response to increases in greenhouse gases (Kattenberg *et al*., 1996). These regions are systematically undersampled by historical coverage of surface temperature observations, so that simulated temperature increases derived using observed coverage tend to underestimate the “true” simulated global-mean temperature increase.

We also looked at the issue of how missing observational data affects estimates of rank-ordering of years by temperature – i.e., which year was the warmest globally, second warmest, *etc.* (Karl *et al*., 1999). For each of the 16 climate change simulations considered here, we ranked the years in order of decreasing global-mean annual-mean temperature anomaly. This was done using both globally complete and masked model output.

In 10 out of 16 simulations, the estimate of the warmest year in the last century based on the masked model output agrees with the “true” answer obtained from the globally complete model data. However, estimates of the three (five) warmest years (including their relative ranking) in the masked and globally-complete model output agree in only 3 (2) of 16 simulations. In two cases, the year that is the warmest based on globally complete model output is not among the three warmest when estimates are made from masked model output. Thus, even though the warmest years occurred during the last 1-2 decades, when observational coverage was relatively good, estimates of the relative ranking of the warmest years are still sensitive to sampling errors induced by incomplete and time-varying coverage of observational data.

Discussion and Conclusions

The causes of the range of difference trends (masked minus global coverage) shown in Figure 2 include differences in the applied forcings, in the simulated response to these forcings, and in the models’ natural internal variability. Response and internal variability differences are likely related to differences in model physics, resolution, spin-up, and flux correction procedures. It may be significant that the two models that show the largest positive difference trends in Figure 2a (CCSR and MPI) also show similar areas of rapid cooling in the Southern Ocean and parts of Antarctica. This cooling may represent low-frequency internal climate variability, or may be an artifact of incomplete model spinup.

The evidence presented here suggests that the observed near-surface temperature trend of ca. 0.6°C over 1900 to 1998 is unlikely to have been significantly overestimated by incomplete and time-varying observed data coverage. This conclusion is consistent with the results of earlier analyses (Jones *et al*., 1997; Karl *et al*., 1994). Based on the climate-change experiments considered here, a slight underestimate of the true trend is a more probable result. This conclusion depends on the realism of the applied forcings, the simulated response to these forcings, and the models’ representation of natural internal climate variability.

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References

Bengtsson, L., Roeckner, E., Stendel, M., Why is the global warming proceeding much slower than expected? *J. Geophys. Res.*, *104*, 3865 (1999).

Boer, G. J., Flato, G. M., Reader, M. C., & Ramsden, D., A transient climate change simulation with greenhouse gas and aerosol forcing: experimental design and comparison with the instrumental record for the 20th century, *Clim. Dyn. 16*, 405-425 (2000a).

Boer, G. J., Flato, G. M., & Ramsden, D., Transient climate change simulation with greenhouse gas and aerosol forcing: projected climate to the 21st century, *Clim. Dyn. 16*, 427-450 (2000b).

Boville, B.A., & Gent, P.R., The NCAR Climate System Model, version one. *J. Climate*, *11*, 1115 (1998).

Emori, S., T. Nosawa, A. Abe-Ouchi, A. Numaguti, M. Kimoto, and Y Nakajima, Coupled ocean-atmosphere model experiments of future climate change with an explicit representation of sulfate aerosol forcing. *J. Meteor. Soc. Japan*, *77*, 1299 (1999).

Gordon, H.B., & O'Farrell, Transient climate change in the CSIRO coupled model with dynamic sea ice. *Mon. Weath. Rev.*, *125*, 875 (1997).

Haywood, J.M., R.J. Stouffer, R.T. Wetherald, S. Manabe & V. Ramaswamy, Transient response of a coupled model to changes in greenhouse gas and sulfate concentrations. *Geophys. Res. Lett.*, *24*, 1335 (1997).

Hirst, A.C., O'Farrell, S.P., & Gordon, H.B., Comparison of a coupled ocean-atmosphere model with and without oceanic eddy-induced advection. Part I: ocean spinup and control integration. *J. Climate, 13*, 139 (2000).

Johns, T.C., R.E. Carnell, J.F. Crossley, J.M. Gregory, J.F.B. Mitchell, C.A. Senior, S.F.B. Tett, and R.A. Wood, The second Hadley Centre coupled ocean-atmosphere GCM: model description, spinup, and validation. *Clim. Dyn*., *13*, 103 (1997).

Jones, P.D., New, M., Parker, D.E., Martin, S., & Rigor, G., Surface air temperature and its changes over the past 150 years. *Rev. of Geophys*. *37,* 173 (1999).

Jones, P.D., Hemispheric surface air temperature variations: a reanalysis and an update to 1993 *J. Climate*. *7*, 1794 (1994).

Jones, P.D., S.C.B. Raper, R.S. Bradley, H.F. Diaz, P.M. Kelly, and T.M.L. Wigley, Northern Hemisphere surface air temperature variations: 1851-1984, *J. Clim. Appl. Met*., *25*, 161-179, (1986a).

Jones, P. D., Osborn, T. J., & Briffa, K. R., Estimating temperature errors in large-scale temperature averages. *J. Climate*, *10*, 2548 (1997).

Jones, P.D., Wigley, T.M.L., & Raper, SCB, Southern Hemisphere surface air temperature variations: 1851-1984, *J. Clim. Appl. Met*., *25*, 1213-1230, (1986b).

Karl, T.R., Knight, R.W., and Baker, B., The record-breaking global temperatures 1997 and 1998: Evidence for an increase in the rate of global warming? *Geophys. Res. Lett.,* 27, 719 (1999).

Karl, T. R., Knight, R. W., & Christy, J. R., Global and hemispheric temperature trends – uncertainties related to inadequate spatial sampling. *J. Climate*, *7*, 1144 (1994).

Kattenberg, A. F. Giorgi, H. Grassl, G.A. Meehl, J.F.B. Mitchell, R.J. Stouffer, T. Tokioka, A.J. Weaver, T.M.L. Wigley, Climate Models – Projections of Future Climate, in Climate Change 1995 The Science of Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds., Cambridge University Press, 1996.

Madden, R. A., Shea, D. J., Branstator, G. W., Tribbia, J. J., & Weber, R., The effects of imperfect spatial and temporal sampling on estimates of the global mean temperature – experiments with model data. *J. Climate, 6*, 1057 (1993).

Manabe, S., & Stouffer, R.J., Low-frequency variability of surface air temperature in a 1000-year integration of a coupled atmosphere-ocean-land surface model. *J. Climate 9*, 376 (1996).

Mitchell, J.F.B., Johns, T.C., Gregory, J.M., & Tett, S.F.B., Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Nature*, *376*, 501 (1995).

Nicholls N, G.V. Gruza, J. Jouzel, T.R. Karl, L.A. Ogallo, and D.E. Parker, Observed climate variability and change. in *Climate Change 1995: The Science of Climate Change*, J. T. Houghton , L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Eds. Cambridge Univ. Press, Cambridge, 1996, pp. 133-192.

Parker, D.E., Jones, P.D. Folland, C.K, & Bevan, A., Interdecadal changes of surface temperature since the late 19th century, *J. Geophys. Res. 99*, 14373 (1994).

Singer, S.F., Comment: Human contribution to climate change remains questionable, *EOS*, *80*, 186 (1999).

Roeckner, E., L. Bengtssonm J. Feichter, L. Lelieveld & H. Rode, Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle. *J. Climate*, *12*, 3004 (1999).

Santer B.D., Wigley, T.M.L., Boyle, J.S., Gaffen, T.J., et al., Statistical significance of trends and trend differences in layer-average atmospheric temperature time series, *J. Geophys. Res.-Atmos*., *105*, 7337-7356 (2000).

Smith, T.M., Reynolds, R.W., & Ropelewski, C.F, Optimal averaging of seasonal sea surface temperatures and associated confidence intervals *J. Climate*, *7*, 949 (1994).

Stouffer, R.J., S. Manabe, and K.Y. Vinnikov, Model assessment of the role of natural variability in recent global warming, *Nature, 367*, 634 (1994).

W.M. Washington, J.W. Weatherly, G.A. Meehl, A.J. Semtner, Jr., T.W. Bettge, A.P. Craig, W.G. Strand, Jr., J. Arblaster, V.B. Wayland, R. James and Y. Zhang, Parallel climate model (PCM) control and transient simulations *Clim. Dyn.* 16, 755 (2000).

Wigley, T.M.L. and S. Raper, Natural variability of the climate system and detection of the greenhouse effect, *Nature, 344*, 324 (1990).

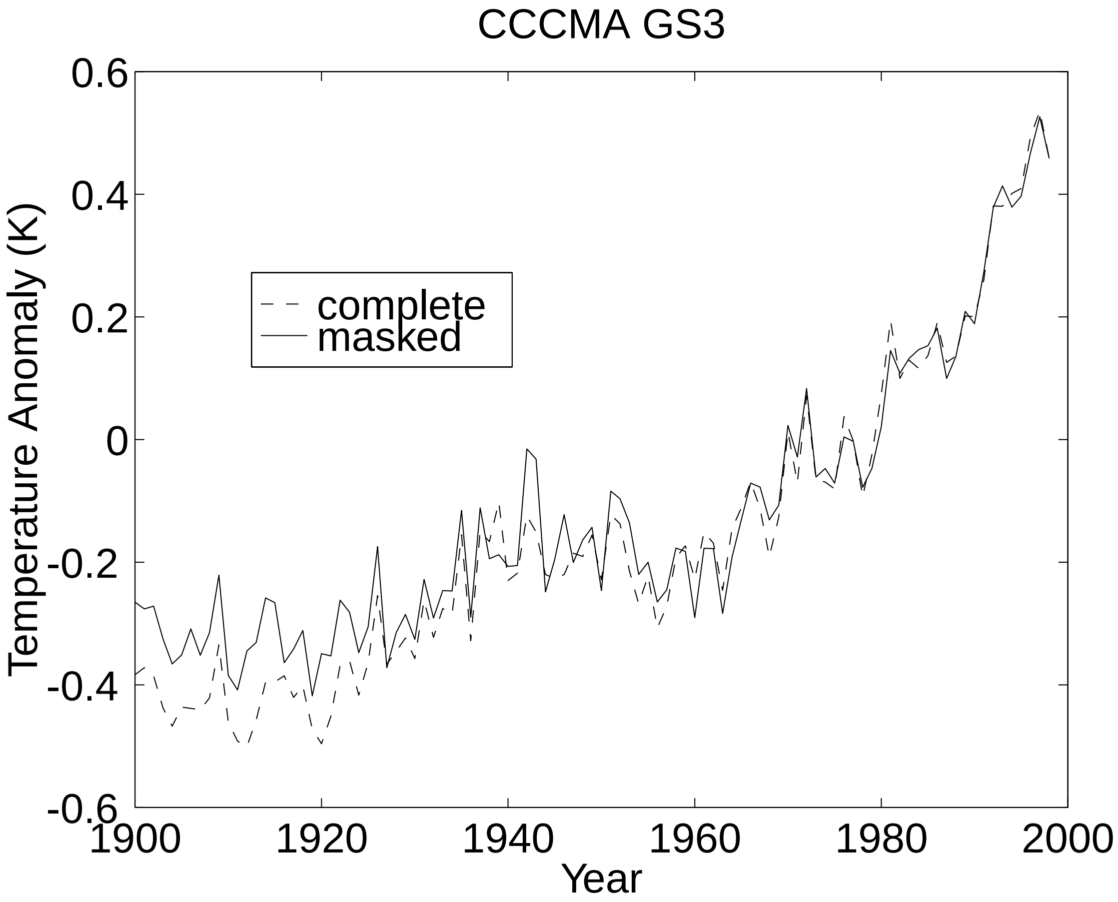

Figure 1: Near-surface temperature anomalies from the CCCMA GS3 integration. Model results are shown for both globally-complete results and for model results masked to „exclude areas where observations are missing. The temperature change during 1900-1998 obtained using historical observational coverage is slightly smaller than the "true" trend computed with globally complete model output (see Fig. 2).

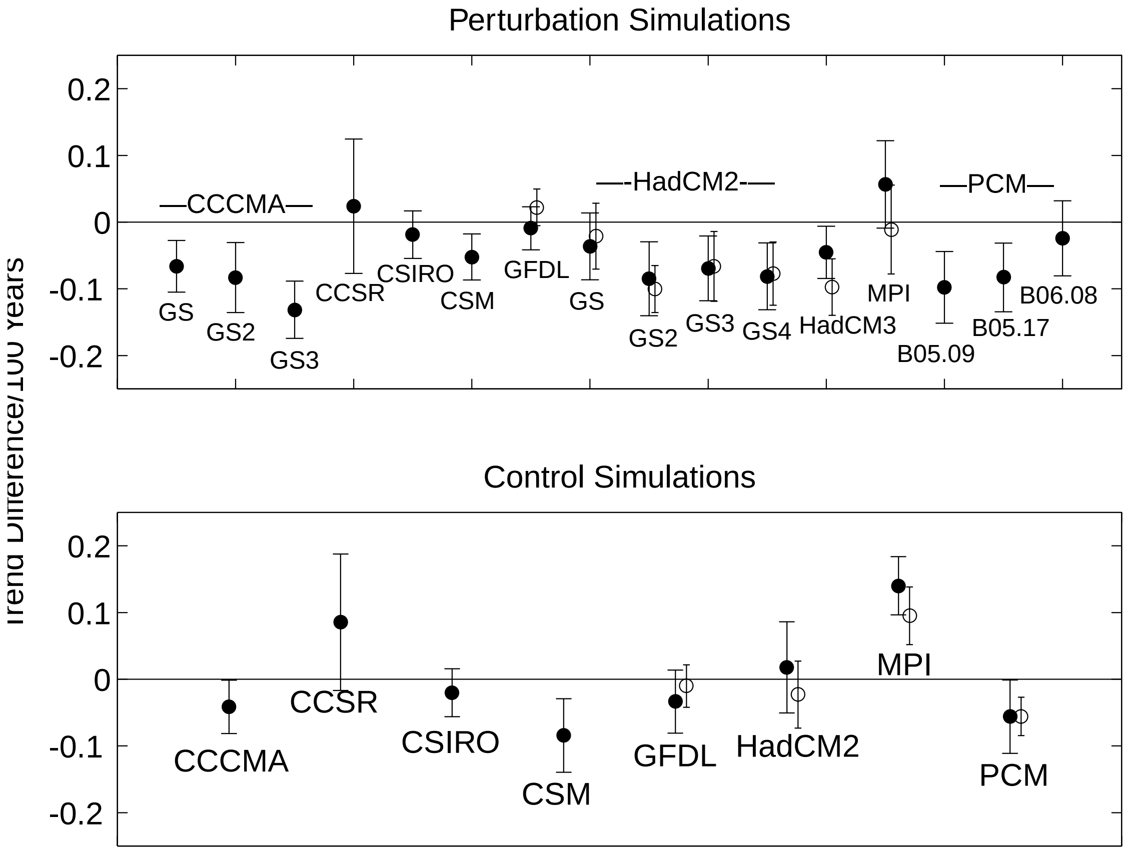

Figure 2: Difference trends (masked minus globally complete model output) and 95% confidence intervals for the climate change simulations (upper panel) and control simulations (lower panel) given in Table 1. Confidence intervals are adjusted for temporal autocorrelation effects, as in Santer *et al.,* (2000). We show difference trends over the period 1899-1998 (except for the CCCMA simulations, where only 99 years were available; see Table 1). For 11 simulations we also considered the 139-year period 1860-1998 (open circles). All difference trends are expressed in degrees C/100 years. Integrations with confidence intervals completely below the zero line have "true" global trends that are significantly larger than the trends estimated with historical coverage.

Table 1: Climate Model Simulations Analyzed.

Institution*	Model	Simulation	Forcings⁄	Dates Analyzed	Reference
CCCMA	CGCM1	control	present climate	99 years	Boer *et al.*
		GS1	GHG + SO_4	1900 - 1998	(2000a,b)
		GS2	GHG + SO_4	1900 - 1998	
		GS3	GHG + SO_4	1900 - 1998	
CCSR	CCSR-98	control	present climate	100 years	Emori *et al.*
			GHG + SO_4	1899 - 1998	(1999)
CSIRO	Mk2	control	present climate	100 years	Hirst *et al.* (2000); Gordon and O Farrell (1997)
		GS	GHG + SO_4	1899 - 1998	
NCAR	CSM	control	present climate	100 years	Boville and Gent
			GHG + SO_4	1899 - 1998	(1998)
GFDL		control	present climate	100 years 139 years	Manabe and Stouffer (1996); Haywood *et al.* (1997)
		GS	GHG + SO_4	1899 - 1998 1860 - 1998	
UKMO	HadCM2	control	present climate	100 years 139 years	Mitchell *et al.* (1995); Johns *et al.* (1997)
		GS1	GHG + SO_4	1899 - 1998 1860 - 1998	
		GS2	GHG + SO_4	1899 - 1998 1861 - 1998	
		GS3	GHG + SO_4	1899 - 1998 1860 - 1998	
		GS4	GHG + SO_4	1899 - 1998 1860 - 1998	
	HadCM3	GS	GHG + SO_4	1899 - 1998 1860 - 1998	
MPI	ECHAM4/OPYC	control	present climate	100 years 139 years	Roeckner *et al.* (1999); Bengtsson *et al.* (1999)
		GSD	GHG + SO_4	1899 - 1998 1860 - 1998	
DOE/NCAR	PCM	control	present climate	100 years 139 years	Washington *et al.* (2000)
DOE/NCAR	PCM	B05.09	GHG + SO_4	1899 - 1998	
		B05.17	GHG + SO_4	1899 - 1998	
		B06.08	GHG + SO_4	1899 - 1998	

* CCCMA: Canadian Centre for Climate Modeling and Analysis; CCSR: Japanese Centre for Climate System Research; CSIRO: Australian Commonwealth Scientific and Industrial Research Organization; NCAR: National Center for Atmospheric Research; GFDL: Geophysical Fluid Dynamics Laboratory; UKMO: United Kingdom Meteorological Office; MPI: Max-Planck Institute for Meteorology; DOE/NCAR: Dept. of Energy/National Center for Atmospheric Research.

CGCM1: Canadian Global Coupled Model, version 1; CCSR-98: Japanese Centre for Climate System Research, version 1998; Mk2: Mark 2; CSM: Climate System Model; HadCM2,3: Hadley Centre for Climate Prediction and Research Coupled Model, versions 2 and 3; ECHAM4/OPYC: ECMWF/Hamburg atmospheric GCM, coupled to Hamburg isopycnal ocean model; PCM: Parallel Climate Model.

CCCMA experiments GS1, GS2, and GS3 have identical forcing, but each starts from slightly different initial conditions. The same applies to the UKMO experiments GS1, GS2, GS3 and GS4. Control simulations have time invariant concentrations of greenhouse gases and sulfate aerosols.

⁄ GHG + SO_4: includes radiative effects of well-mixed greenhouses gases and direct effects of anthropogenic sulfate aerosols.