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A method for obtaining pre-twentieth century initial conditions for use in climate change studies

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Abstract A method is proposed to initialise coupled atmosphere-ocean general circulation models (AOGCMs) developed to study climate change on multi-century time scales. The method assumes that current generation AOGCMs are developed and evaluated using present-day radiative forcing and near present day oceanic initial conditions. To find pre-twentieth century initial conditions, we propose that the radiative forcing be run backwards in time from the present to the desired starting date. The model should then be run for 3–5 centuries with the radiative forcing held constant at the desired date. In our tests, instantaneously switching to pre-twentieth century radiative forcing did not save computational time. When a sufficiently stable pre-twentieth century condition is achieved, the coupled system can be integrated forward to the present and into the future. This method is a first step toward the standardization of AOGCM initialization and suggests a framework for AOGCM initialization for the first time. It provides an internally consistent set of pre-twentieth century initial conditions, although they will vary from model to model. Furthermore, it is likely that this method will yield a fairly realistic present-day climate in transient climate change experiments of the twentieth century, if the model biases are not too large. The main disadvantage of the method is that it is fairly computationally expensive in that it requires an additional 4–6 centuries of model integration before starting historical twentieth century integrations. However, the relative cost of this technique diminishes as more simulations are conducted using the oceanic initial condition obtained using our method.

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1 Introduction

The initialization of coupled atmosphere-ocean climate models (AOGCMs) has been a long-standing problem in models used to study climate change on multi-century time scales (Moore et al. 2001). To perform simulations of the twentieth century and into the future, modellers must start with an initial equilibrium prior to extensive industrialization (typically near year 1850). If extensive observational data sets were available, modellers would be able to evaluate an 1850 simulation, starting from 1850 initial conditions and driven by 1850 radiative forcing, against this data record. They would then use the historical time series of the various radiative forcing factors to simulate the climate from 1850 to the present. Unfortunately, such pre-twentieth century observations are not available so that modellers have had to develop various ad hoc methods of initializing their AOGCMs. With this study, we propose a new method to obtain the pre-twentieth century initial conditions.

Due to its large heat capacity, much of the long-term memory of the climate system is found in the ocean. Weaver et al. (2000) demonstrated that the present-day oceanic temperature and salinity structure is influenced by changes in radiative forcing, which have occurred over the past 1000 years or so. They further point out that the typical AOGCM development and evaluation process, wherein a present-day simulation is obtained with perpetual present-day radiative forcing and subsequently compared with present-day observations, fundamentally assumes that the present-day climate system is in radiative equilibrium with the present-day radiative forcing. This is clearly not the case (Ramaswamy et al. 2001). Weaver et al. (2000) went on to show that neglecting this fact in initializing the coupled AOGCMs can influence the projection of future climate changes. Therefore, it is important that the climate community develop standardized methods to initialize climate models.

In the past, climate modellers have used a variety of methods to find initial conditions for their coupled AOGCMs. Stouffer and Dixon (1998) summarized these methods and developed a system for categorizing them; we adopt their nomenclature herein. Typically, models that utilize flux adjustments, use methods in which the atmosphere and ocean component models are each integrated to a statistical equilibrium before coupling (see Weaver and Hughes 1996 for a discussion of the development and use of flux adjustments). The initial conditions for the AOGCM are then obtained from points near the end of the component integrations. Other AOGCMs have been developed that do not require flux adjustments to have long, relatively stable control integrations. These models can either start from prior component model integrations, as described already, or they may use observational data sets as initial conditions.

Numerical Weather Prediction centres use models to produce relatively short-term forecasts (days to weeks, sometimes forecasts as long as one year ahead). These models are initialized using three-dimensional atmospheric fields, land surface data and perhaps oceanic near surface temperatures. The atmospheric component of AOGCMs can also be initialized using these data sets, thereby allowing synoptic atmospheric initial conditions to be determined relatively easily. However, as noted above, the real problem in AOGCM initialization for long-term climate simulations is the oceanic initial conditions. Three-dimensional synoptic oceanic data and sea-ice data covering the whole globe are just now becoming available. In the absence of synoptic oceanic data, modellers have used the various observational based data sets such as those developed by Levitus and collaborators (e.g. Levitus 1982; Levitus et al. 1994a,b, 2002). These data sets represent an average of all the oceanic data available at the time the data set was produced. Therefore, they provide a representation of the climatological average over the last 50 years or so.

AOGCMs are normally developed using near present day radiative conditions, that is, the concentrations of the various atmospheric constituents, which are radiatively active, are held fixed near their present-day values. The atmospheric initial conditions are either observationally based or obtained from some prior integration of the atmospheric model integrated using prescribed present day sea surface temperatures and sea-ice conditions. The oceanic initial conditions typically are obtained from Levitus data sets. Usually an integration using an ocean model alone is performed starting from the Levitus data. This integration is typically less than 100 model years in length, allowing some time for the density field to adjust and for the ocean currents to adjust to the input density field. However this adjustment period is not normally complete before the integration is stopped. The conditions from the end of this ocean-only integration are then used as oceanic initial conditions for the AOGCM integrations.

To perform historical simulations where the radiative forcing is set to a time before world-wide observational measurements are available, modellers must do something ad hoc given that the oceanic conditions already described represent a near present day climatology. Many different techniques have been used. One method is to assume the present-day radiative forcing is the pre-industrial radiative forcing. All the radiative changes since pre-industrial times are applied to the model as an additive offset to the present day conditions (e.g. Manabe et al. 1991, Mitchell et al. 1995). In another case (HadCM3 — Stott et al. 2000), the radiative forcing was just reset to near 1850 conditions using near present day Levitus oceanic initial conditions. They found that their model did not drift very much when initialized using this mixture of present day and 1850 conditions.

Neither of these methods is very satisfactory. In the first case, as the model is integrated toward present-day radiative forcing conditions from the pre-industrial conditions, the climate will be warmer than present-day. One will only be able to compare observed and modelled climate anomalies, not the raw values. The second method suffers because in general, a model coupled in this manner will suffer from climate drifts. The developers were fortunate to find a relatively good, stable control integration using this technique.

At the October 7–10, 2002 meeting of the World Climate Research Program (WCRP) Working Group on Coupled Modelling (WGCM) held in Victoria, British Columbia, the AOGCM initialization problem was discussed. As a result of this meeting it became apparent that new initialization methods must be developed and standardized. The method presented here is a direct outgrowth of these discussions and represents a first step towards this goal.

The outline for the rest of the paper is as follows. The description of the method is presented in the following section. The description of the University of Victoria (UVic) model used to test various issues using the method and the results of these tests are presented in the subsequent two sections. A discussion of the advantages and disadvantages of the method and our recommendations are presented in the final section.

2 Method description

Our initialization method assumes the following as a starting point. We recognize that most climate models are now developed using Levitus oceanic data sets as the oceanic component initial conditions. As noted in the Introduction, the atmospheric three-dimensional initial conditions are not as important as the atmosphere equilibrates with the upper ocean on a relatively rapid time scale. The atmospheric initial conditions can be obtained either from observations or a multi-year integration of the atmospheric component model. For example, the atmospheric integration can be an AMIP integration, (Atmosphere Model Intercomparison

Project, see AMIP web site for more details on how to set up and perform this integration http://www-pcmdi.llnl.gov/amip/amiphome.html). We further assume that the modelled coupled system is initially in a near equilibrium with the present-day radiative forcing. Many of the newest AOGCMs are designed not to use flux adjustments, however, flux adjusted models can also use our method.

The exact date for the desired initial conditions is not too important for the discussion presented here. Dixon and Lanzante (1999) have shown that starting in the middle of the 1800s minimizes the influence of the initial conditions on the twentieth century simulation. Here we will use an 1850 initial condition to illustrate our method, recognizing that many groups use a start date very close to 1850.

In order to produce 1850 conditions, we propose that a particular AOGCM be initialized from a present day control integration and then integrated back to 1850 with decreasing radiative forcing. Once 1850 radiative conditions are reached, they should be held constant and the AOGCM integrated for a period of time using those 1850 radiative conditions. This allows the climate system to gradually, come into adjustment with the 1850 radiative forcing. The integration where the radiative conditions are held constant at 1850 can become a control integration for the perturbation integrations that follow. After a period of time, forward integrations can begin starting from the 1850 control integration with the radiative forcing going forward towards present day values and then into the future. Starting from various points in the 1850 control integration, an ensemble of integrations can be made simulating the twentieth century and future conditions.

In order to make the following discussion clearer, we need to tag these integrations with shorthand names for use in the discussion that follows. The integration from present day back to 1850 radiative forcing conditions is labelled "1850BACK". The special case where the radiative forcing is instantaneously switched back to 1850 conditions is called the "1850INSTANT" case (this is an 1850BACK integration of 0 years in length). The integration where the radiative forcing is held constant at 1850 is called "1850CONTROL". The integration(s) starting from 1850CONTROL using radiative forcing going from 1850 toward present is called a "historical" twentieth century integration. The simulation obtained from a historical twentieth century integration is normally compared to the observations of the twentieth century climate.

To summarize, this method uses two transient climate integrations where only one has been used in the past. The common transient integration is the "historical" simulation of the twentieth century climate where the radiative forcing goes from 1850 conditions toward present day. In our method, the new transient integration is 1850BACK, which continues into 1850CONTROL. Note that 1850CONTROL is just a continuation of the 1850BACK integration with the 1850 radiative conditions held constant.

We recommend that the historical twentieth century integration begins after 3 to 5 centuries into the 1850CONTROL integration where the 1850 conditions held fixed. This is long enough to allows that the simulated climate time to adjust to the 1850 radiative forcing. We note however that this adjustment will not be complete. Since we do not know the radiative imbalance present in the observed coupled system at 1850, it seems unwise to integrate the model more than 1000 model years needed to reach a near equilibrium 1850 state.

Near the beginning of the 1850CONTROL integration, the climate will be warmer than an equilibrated 1850CONTROL integration where the coupled system is allowed to equilibrate to the 1850 radiative conditions. This is the result of the model climate approaching the 1850 from relatively warm conditions (present-day).

As presented, two main issues in applying this method are not well defined. One is how to go from the present-day radiative conditions back to 1850 radiative conditions. The second issue is how long to run the 1850CONTROL integration before starting the historical simulations of the twentieth century. We use the UVic Earth System Climate Model (ESCM) to begin to answer these questions. One of the main advantages of this model is that it is very computationally efficient, allowing many long integrations to be performed.

3 Model description

Since its original conception in Fanning and Weaver (1996), the UVic ESCM has undergone significant development. It now consists of a three-dimensional ocean GCM coupled to a thermodynamic/dynamic sea-ice model, an ocean carbon cycle model, a dynamic energy moisture balance atmosphere model, a thermo-mechanical land-ice model, a land surface model and a terrestrial vegetation and carbon cycle model (Weaver et al. 2001; Matthews et al. 2003, 2004; Meissner et al. 2003b; Ewen et al. 2004). A reduced complexity atmosphere model is used for computational efficiency. Atmospheric heat transport is parametrized through diffusion, and moisture transport is accomplished through advection and diffusion, with precipitation occurring when the relative humidity exceeds 85%. The atmospheric model includes a parameterisation of water vapor/planetary longwave feedbacks, although the radiative forcing associated with changes in atmospheric CO_2 is externally imposed as a reduction of the planetary long wave radiative flux. A specified lapse rate is used to reduce the surface temperature over land where there is topography. The model uses prescribed winds to obtain its present-day climatology, and a dynamical wind feedback is included that exploits a latitudinally varying empirical relationship between atmospheric surface temperature and density. The ocean component of the coupled model is a fully nonlinear three-dimensional

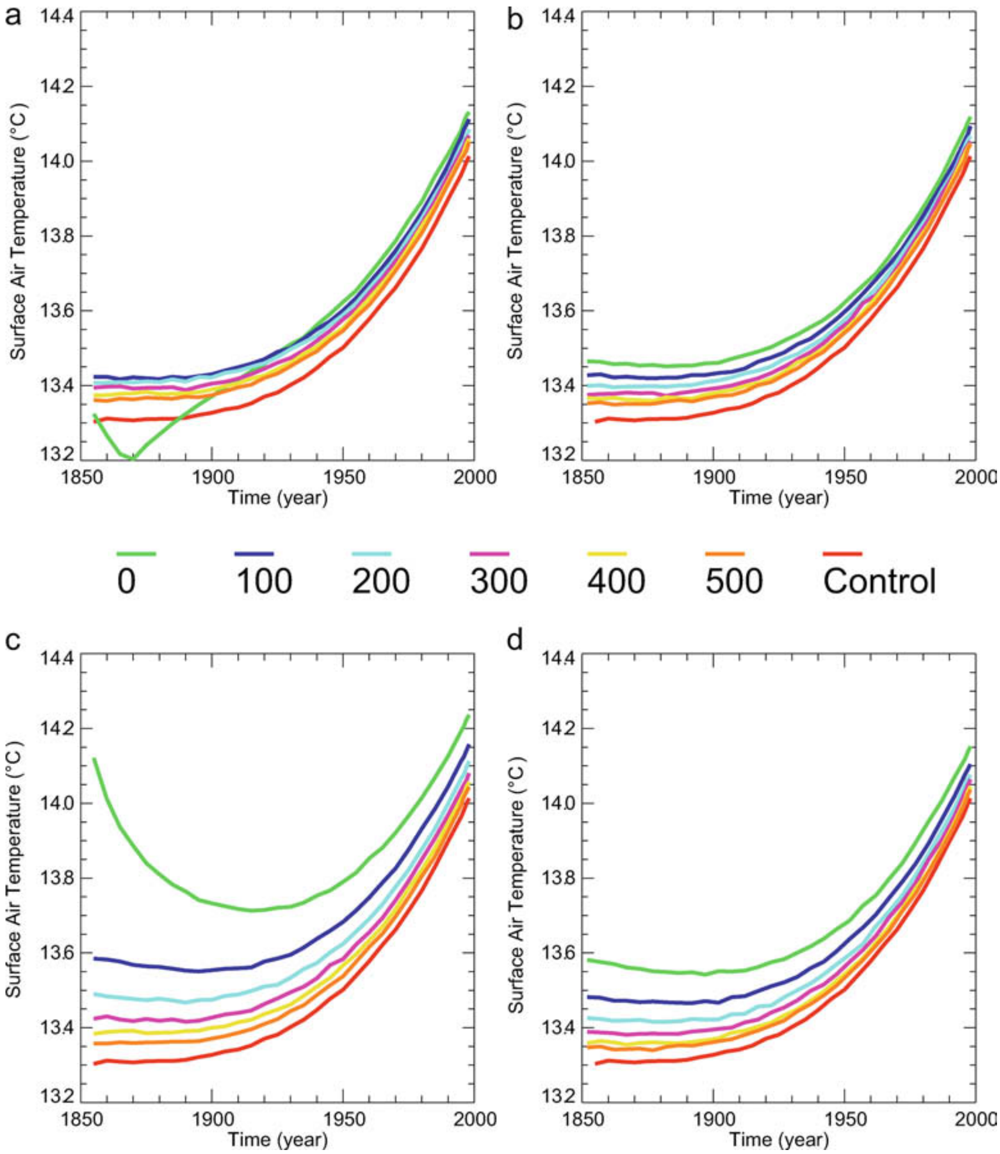


Fig. 1 Time series of the globally-averaged surface air temperature (°C) from 1850 to 1998. **a** ''Instantaneous switch-back'' case where Levitus data are used in the 1850 initial condition. **b** ''Backwards integration'' case where Levitus data are used in the 1998 initial condition and the model is then integrated back to 1850; **c** ''Instantaneous switch-back'' case where the year 1998 model equilibrium is used as an 1850 initial condition; **d** ''Backwards integration'' case where the model starts at a year 1998 model equilibrium and is then integrated back to 1850. The *red line* represents the control or ''perfect model'' experiment where the climate is in equilibrium with the 1850 forcing prior to integration until year 1998. The *green line* represents the case where the twentieth century integration immediately starts from the 1850 conditions. The *dark blue*, *light blue*, *pink*, *yellow* and *orange lines* show experiments started after 100, 200, 300, 400 and 500 years of integration under 1850 radiative forcing conditions prior to commencing the twentieth century integration, respectively

ocean GCM with a global resolution of a 3.6° (zonal) by 1.8° (meridional) and 19 vertical levels, that includes an option for a new brine-rejection parametrization (Duffy et al. 1999, 2001). The coupled model incorporates a dynamic/thermodynamic sea-ice model (Bitz et al. 2001, Holland et al. 2001). An elastic-viscous-plastic rheology (Hunke and Dukowicz 1997) is used to represent dynamics and various options are included for the representation of sea-ice thermodynamics and thickness distribution.

The philosophy underlying the development of the UVic ESCM is that on time scales greater than a decade, the ocean, its horizontal gyre structure, and its ability to transport heat and freshwater are key components of the climate system (Stouffer 2004). The coupled model has been extensively and successfully evaluated against both contemporary climate observations (Weaver et al. 2001) as well as paleo proxy records (Weaver et al. 1998; Schmittner et al. 2002; Meissner et al. 2003a). The UVic model is built in a modular fashion much like its ocean component, the GFDL MOM model (e.g. Griffies et al. 2003). As this application is focusing exclusively on twentieth century processes, we turned off the carbon cycle, continental ice sheet and terrestrial vegetation and

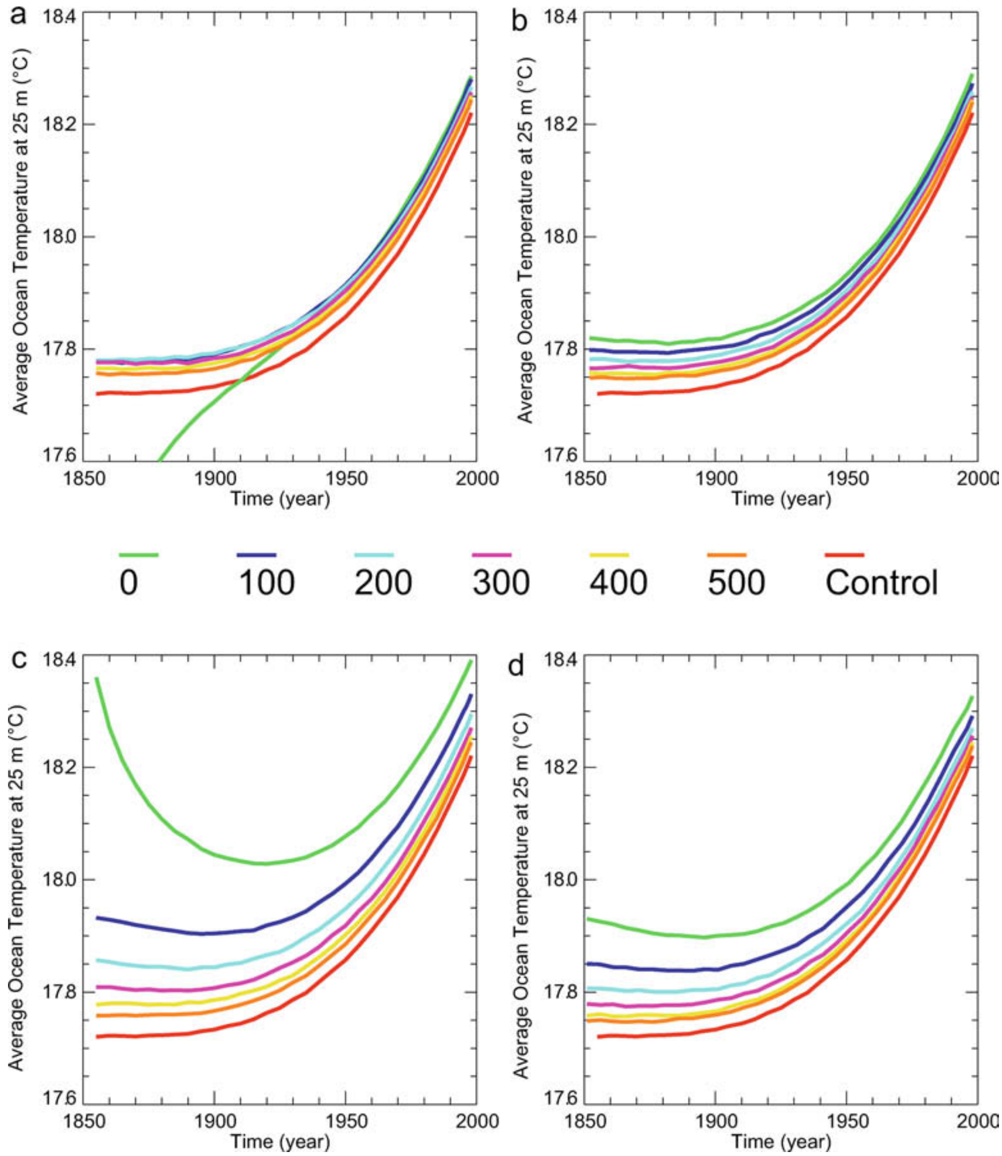


Fig. 2 As in Fig. 1 but for sea surface temperature (°C) represented by temperature at the top level of the ocean component of the coupled model

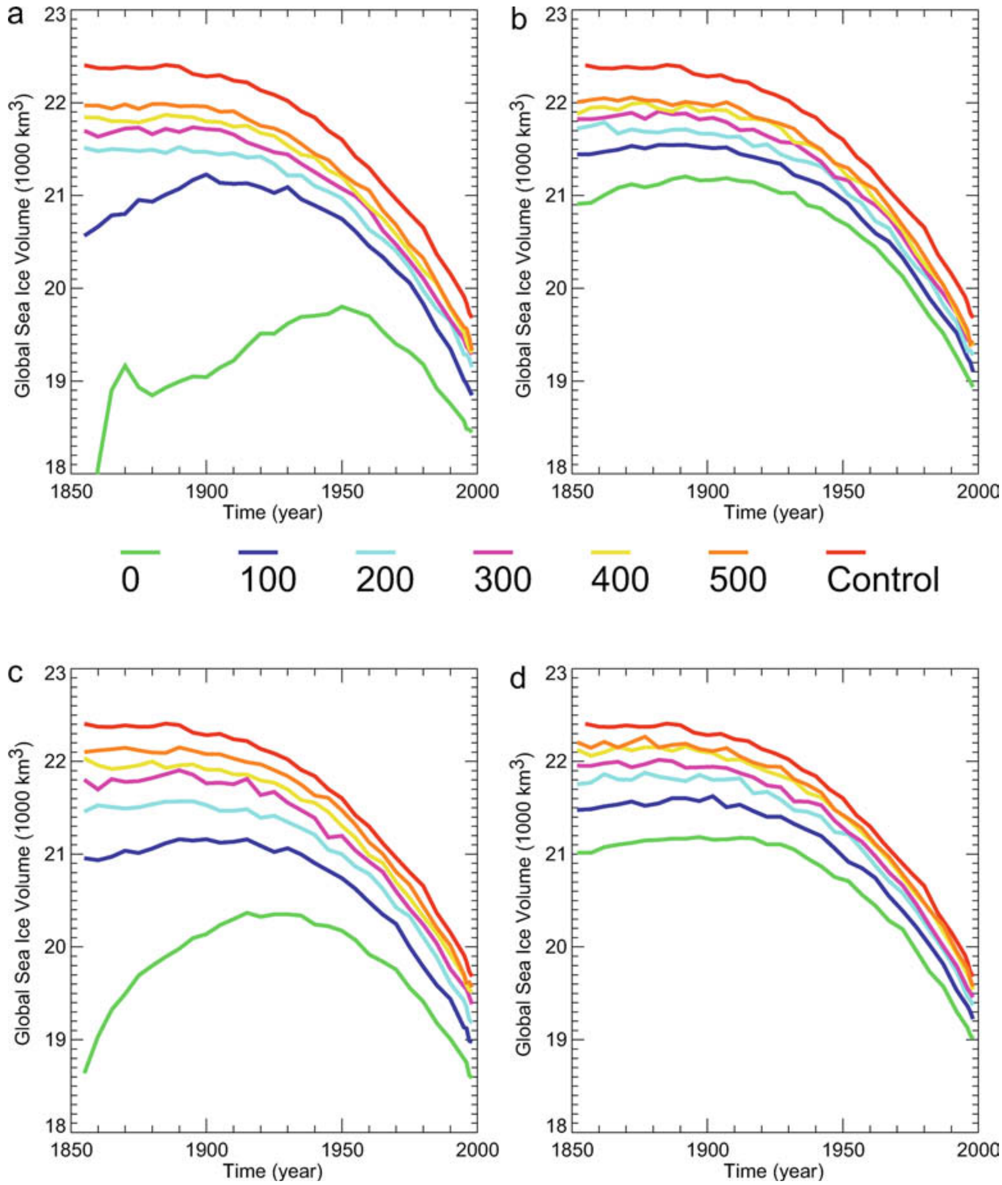
land surface subcomponent models. The wind feedback option was also not used in the model experiments (Weaver et al. 2001).

4 Model results

To begin, we develop an integration where the radiative forcing is set to present-day conditions and the oceanic initial conditions are interpolated from the observationally based Levitus data sets. As noted earlier, this is similar to the method used by many modelling groups today to develop their AOGCMs. The present day radiative forcing returns towards 1850 conditions using two different methods: the 1850BACK integration and the 1850INSTANT assumption. In 1850INSTANT, the radiative forcing is instantaneously switched back to 1850 conditions from the present-day. In this case, the integration is 0 years in length, a savings of about 150 years of integration time when compared to the 1850BACK case. In a second method (1850BACK), the model is integrated backwards in time towards 1850. In this case, the 1850BACK integration is about 150 years in length. In both cases, the 1850CONTROL integration (the integration where the 1850 radiative conditions are held constant) continues from the end of the 1850BACK integration or 1850INSTANT assumption. We then compare historical integrations (cases where the radiation runs from 1850 towards present-day) starting from various points in the 1850CONTROL integration. These points start 0, 100, 200, 300, 400, 500 years into the 1850CONTROL integration. We also compare one historical control integration, which starts after allowing the model to reach a near equilibrium state with the 1850 radiative conditions.

The globally averaged surface air temperature (SAT; Fig. 1) and sea surface temperature (SST; Fig. 2) warm, and the globally averaged sea-ice volume (Fig. 3)

Fig. 3 As in Fig. 1 but for global sea ice volume (10^3 km^3)



decreases throughout the twentieth century in all the integrations as expected. For some of the experiments where the model is integrated for a relatively short time at the 1850 conditions in the 1850INSTANT case, the SAT initially cools and sea ice increases near the beginning of the perturbation run. This occurs because the climate system does not have enough time to respond to the changes in radiative forcing. In these cases, the raditive forcing is instantaneously switched back to 1850 conditions and the 1850CONTROL integration is also relatively short. These integrations will not be included in the discussion that follow. For the rest of the integrations, the climate gradually warms in response to the increasing radiative forcing as one would expect. These integrations will now be discussed.

The SAT, SST and sea-ice volume time series indicate that the differences between the ''instantaneous switch-back'' case (Figs. 1a, 2a, 3a) and the ''backwards integration'' case (Figs. 1b, 2b, 3b) are relatively small. The 1850INSTANT case, of course, saves 150 model years of integration compared to the 1850BACK case as the ''instantaneous switch-back'' case immediately jumps back from the present-day conditions to 1850, whereas in the 1850BACK case the model is integrated over the whole time period: present day to 1850 (150 years). The careful comparison of the results presented in Figs. 1–7 and Tables 1 and 2, however, indicates that the 150 year time savings in the ''instantaneous switch-back'' is lost in that one needs to run longer with the 1850 radiative conditions held constant to achieve similar accuracy over the twentieth century. In the end, it seems that the total time to produce similar results is about the same between the switch-back case and the running time backwards to 1850 case.

By integrating the 1850CONTROL about 300–400 years with the 1850 radiative condition held constant in the ''backwards integration'' case (or 400–500 years in the ''instantaneous switch-back'' case), the

Table 1 Differences at year 1998 between the various experiments and the historical control or "perfect model" experiment

	Length (years)	SAT (°C)	SST (°C)	Sea Ice (10^6 m^3)	AMO (Sv)	T 1528 m (°C)	T 5396 m (°C)	Sea level (cm)
Instantaneous Switch Back								
Control	148	14.01	18.22	19.68	18.21	2.528	0.821	4.90
0	148	0.12	0.07	–1.23	2.45	0.152	0.213	–1.58
100	248	0.10	0.06	–0.83	1.97	0.114	0.209	–3.34
200	348	0.07	0.05	–0.53	1.16	0.083	0.183	–5.06
300	448	0.06	0.04	–0.40	0.82	0.057	0.153	–6.46
400	548	0.05	0.03	–0.38	0.64	0.037	0.121	–7.57
500	648	0.04	0.02	–0.35	0.55	0.021	0.093	–8.44
Backwards Integration								
Control	148	14.01	18.22	19.68	18.21	2.528	0.821	4.90
0	296	0.11	0.07	–0.74	1.70	0.124	0.208	–3.27
100	396	0.08	0.05	–0.58	1.12	0.086	0.180	–5.13
200	496	0.05	0.04	–0.40	0.77	0.057	0.149	–6.58
300	596	0.04	0.03	–0.30	0.63	0.035	0.118	–7.69
400	696	0.03	0.02	–0.30	0.55	0.019	0.091	–8.56
500	796	0.03	0.02	–0.25	0.44	0.006	0.068	–9.24

The top half of the table gives results for the "Instantaneous switch-back" experiments and the bottom half for the "Backwards integration" experiments. Row 2 provides the value of the particular variable at year 1998 from the historical control experiment. Column 1 gives the experiment as indicated in Figs. 1–7 (i.e., the number represents the number of years the model is integrated under 1850 radiative forcing), whereas column 2 gives the total integration in years to reach the present (year 1998). Columns 3–9 give the error for each experiment from the value obtained in the control experiment (row 2). SAT: surface air temperature (Fig. 1); SST: sea surface temperature (Fig. 2); Sea Ice: sea ice volume (Fig. 3); AMO: maximum value of the Atlantic meridional overturning (Fig. 4); T 1528 m: potential temperature at 1528 (Fig. 5); T 5396 m: potential temperature at 5396 m (Fig. 6); Sea level: Steric sea level rise (Fig. 7). The sea level data in the last column is calculated at 1998 relative to the initial condition which includes initialization of the ocean with Levitus data.

Table 2 Difference in the trend over the years 1991–1998 between the various experiments and the control or "perfect model" experiment

	Length (years)	SAT (°C/c.)	SST (°C/ c.)	Sea Ice (10^6 m^3 /c.)	AMO (Sv/c.)	T 1528 m (°C/c.)	T 5396 m (°C/c.)	Sea level (cm/c.)
Instantaneous Switch Back								
Control	148	1.06	0.78	–5.26	4.14	0.076	0.002	8.13
0	148	0.87	0.71	–1.16	–1.77	0.026	0.031	6.67
100	248	0.90	0.75	–4.04	4.73	0.038	–0.007	6.85
200	348	1.08	0.72	–4.40	–0.27	0.059	–0.013	7.11
300	448	0.98	0.67	–2.89	–0.42	0.061	–0.017	7.31
400	548	1.12	0.81	–4.37	–1.73	0.061	–0.016	7.52
500	648	1.19	0.76	–7.90	–0.79	0.066	–0.013	7.65
Backwards Integration								
Control	148	1.06	0.78	–5.26	4.14	0.076	0.002	8.13
0	148	1.07	0.79	–3.53	5.09	0.035	–0.008	6.73
100	248	1.19	0.76	–4.91	1.25	0.058	–0.015	7.07
200	348	0.81	0.63	–1.40	–0.50	0.059	–0.017	7.33
300	448	0.71	0.59	–2.35	–0.58	0.071	–0.015	7.48
400	548	0.84	0.70	–4.10	–1.00	0.058	–0.013	7.65
500	648	1.34	0.86	–3.85	–0.79	0.068	–0.011	7.71

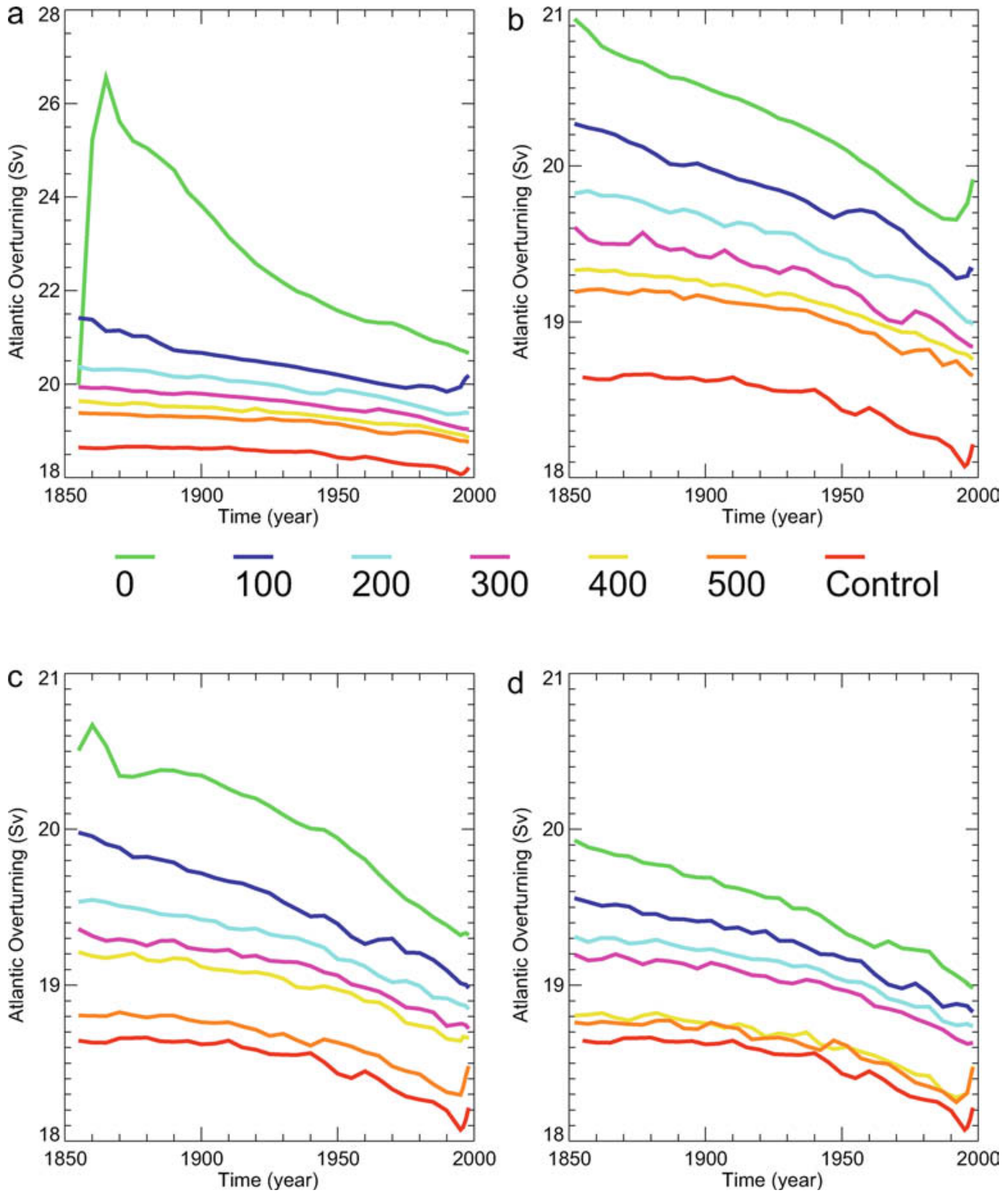
All trends are reported as per century
(/c.). Row 2 provides the trend per century of the particular variable over the years 1996–1998 from the historical control experiment.

time series of SAT (Fig. 1), SST (Fig. 2) or sea ice volume (Fig. 3) are similar to the historical control integration.

It is interesting to note that the curves in Figs. 1–3 tend to converge towards the end of the integrations (present day). As noted later, this convergence is smaller for variables taken from deeper levels of the ocean. As shown by Stouffer (2004), this is related to the very long response time scales (centuries or longer) found in the deep ocean. The varying response times found in the climate system has important implications for the understanding of both past and future climate changes. The smaller rate of convergence is seen for the Atlantic Meridional Overturning (AMO; Fig. 4), potential temperature in the deep ocean (Figs. 5 and 6) and hence steric sea level rise. The steric sea level rise (Fig. 7) represents the integral of all the temperature changes in the water column. It can take thousands of years for sea level changes to come into equilibrium following a change in radiative forcing.

The AMO curve (Fig. 4), where the model is run for 4 or 5 centuries using the 1850 radiative conditions in the "backwards integration" case (or five centuries in the "instantaneous switch-back"), is fairly close to the control integration starting from the equilibrium 1850 conditions. One notes that there is a clear separation

Fig. 4 As in Fig. 1 but for the maximum strength of the Atlantic meridional overturning (Sv; $1\text{Sv} = 10^6\ \text{m}^3\ \text{s}^{-1}$)



from the integrations where the time using the 1850 radiative forcing is shorter than that noted already (Fig. 4; Tables 1 and 2).

For the deep ocean potential temperatures (Figs. 5 and 6) and the steric sea level rise (Fig. 7) there is a clear separation for all the integrations. This is due to the very long response time scales found in the depth ocean noted. Unfortunately, computer resources are not available to find the equilibrium conditions for the control integrations of just about any AOGCM. Indeed, we know of no case where stable control integrations are found for sea level rise using state-of-the-art AOGCMs. To get around this problem, steric sea level rise is normally presented as an anomaly from the control integration where like time periods are differenced to generate the sea level rise time series. Therefore, what matters here is that the shape of the curve for a given integration. Again, the integrations using the 1850 radiative conditions for 4 or 5 centuries in the "backwards integration" case (or five centuries for the "instantaneous switch-back" case) are similar to each other, indicating the influence of the initial conditions and start procedure are diminishing.

As mentioned earlier, the development and evaluation process for most AOGCMs involves a present-day simulation, obtained with perpetual present-day radiative forcing, and a comparison with present-day observations. This approach fundamentally assumes that the present-day climate system is in radiative equilibrium with the present-day radiative forcing. Given that it is impossible to evaluate AOGCMs against extensive 1850 data sets, the current approach to model development evaluation is unlikely to change in the near future. Our "backwards integration" methodology described has the added advantage that it allows for an enhanced model evaluation technique. The twentieth century ocean

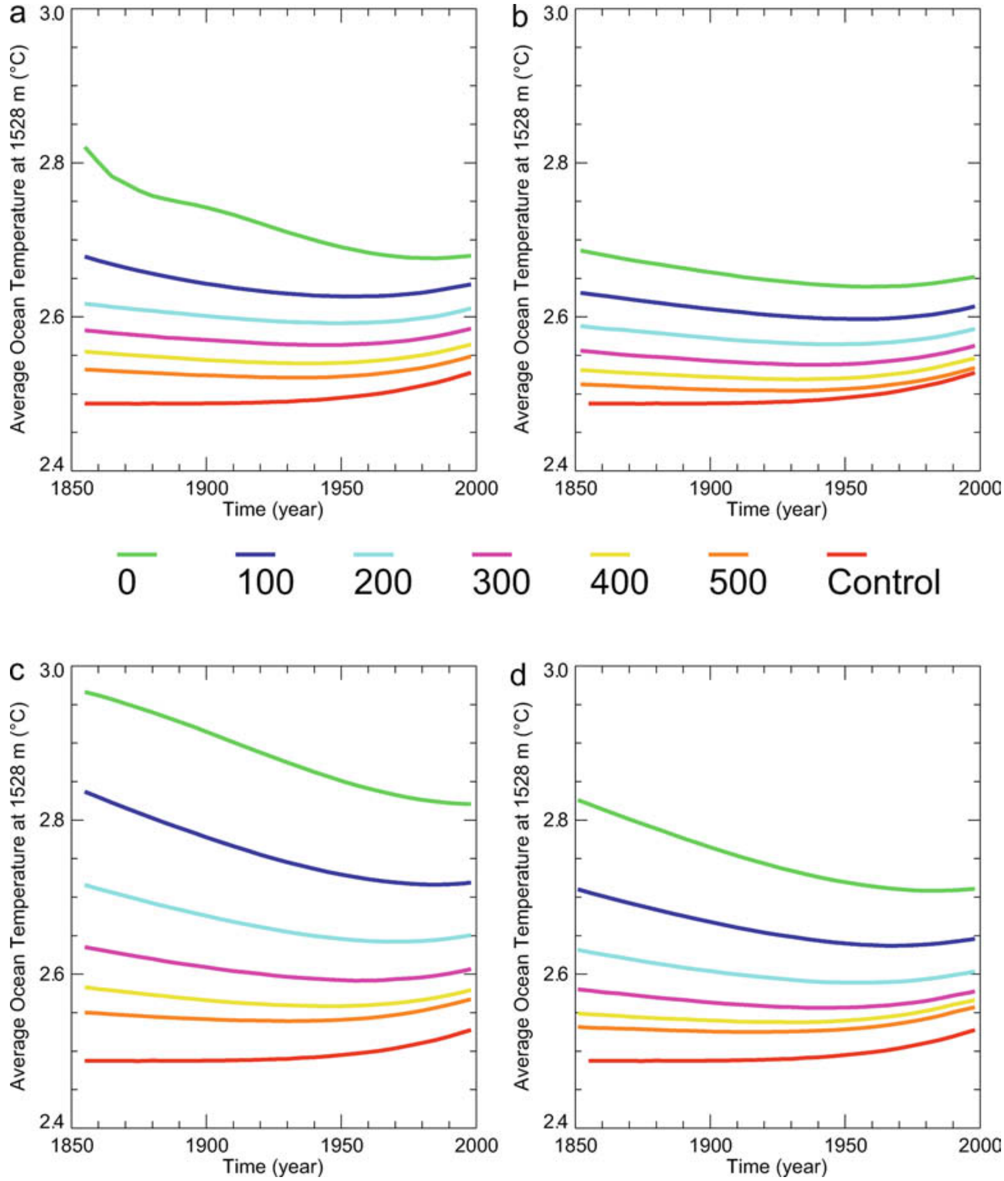


Fig. 5 As in Fig. 1 but for the potential temperature (°C) at a depth of 1528 m

climate obtained in the latter half of ''historical'' twentieth century integration can be compared with the Levitus observational data set more directly.

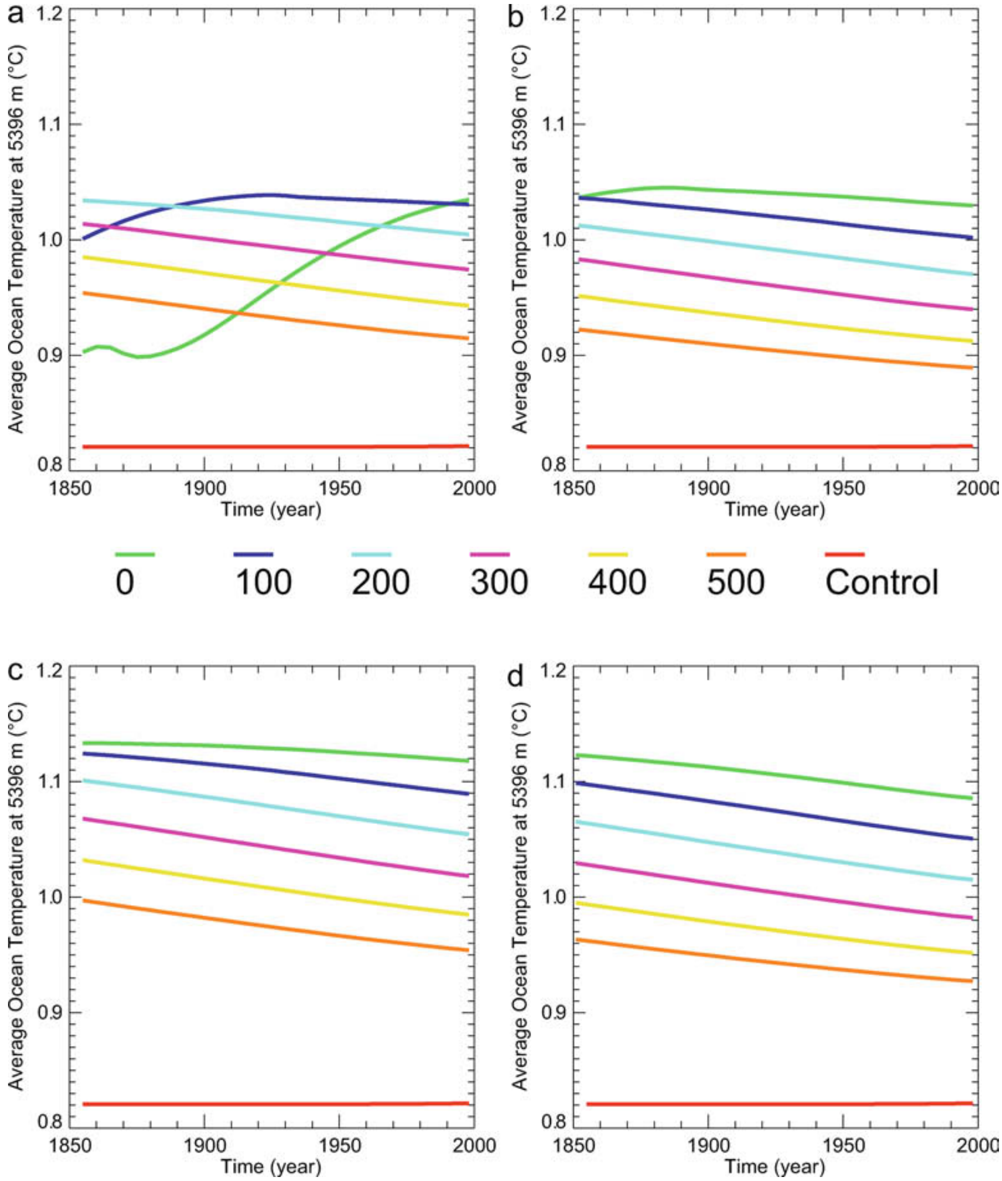
To complete our analysis we perform a second experiment by integrating the UVic model for several thousand years to equilibrium under perpetual 1998 radiative forcing. Instead of Levitus initialization we now use this equilibrium 1998 simulation as a starting point for our backward integration and instantaneous switch back experiments. The purpose of doing these experiments is that it allows a more direct comparison with our ''perfect model'' historical control integration which starts from an 1850 equilibrium climatology obtained under 1850 radiative forcing. Here we assume the model responses are completely realistic. This test allows a comparison of the two different sets of initial conditions (Levitus and equilibrium values) using our method.

All experiments conducted using the 1998 equilibrium as a starting point are analogous to those which used Levitus data as an initial condition for the ocean. The results from these experiments appear as the c) and d) panels of Figs. 1–7 and in Tables 3 and 4. Taken together the results of these experiments lead to the same conclusions as obtained with Levitus initialization suggesting that the Levitus initialization approach, which saves computational time, is a preferred method for AOGCM initialization of the present-day climate. As noted earlier the length of time for the adjustment of the currents to the density fields in a preliminary ocean-only integration is still an unresolved issue.

5 Discussion

A method is proposed to find pre-twentieth century initial conditions for use in AOGCMs, developed to study climate change on multi-century time scales. The method assumes that current generation AOGCMs are

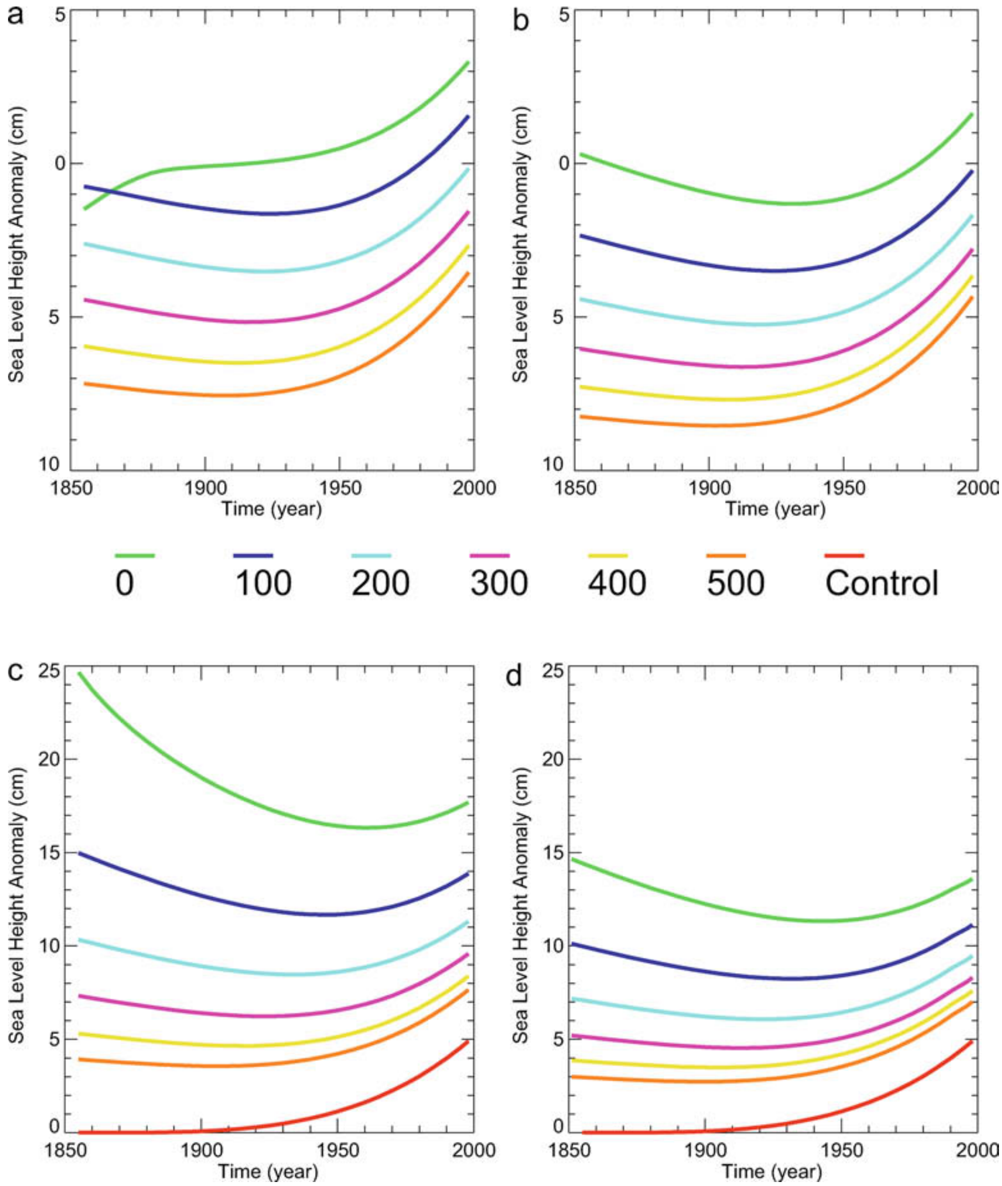
Fig. 6 As in Fig. 1 but for the potential temperature (°C) at a depth of 5396 m



developed using present-day radiative forcing conditions and present-day oceanic climatology as initial conditions. To find the pre-twentieth century oceanic initial conditions, we propose that the AOGCM be integrated backwards in time from the present day to the desired starting date with decreasing radiative forcing. The model should then be integrated for 3 to 5 centuries with the radiative forcing conditions held constant at the pre-twentieth century values. Many modelling groups have chosen a starting date near 1850 for their historical radiative forcing integrations. For much of the discussion presented, we used 1850 as a practical example of a pre-twentieth century starting date.

The method presented here only works for relatively small changes in radiative forcing. Other initialization methods need to be used in cases where the changes in radiative forcing are large. The problem, as noted in the Introduction, lies in the long oceanic time scales inherent in the climate system. In simulations of the Last Glacial Maximum (LGM), AOGCMs are normally initialised with present day conditions. It takes several millennia for the Holocene warmth to leave the ocean. This has lead to the development of a number of novel initialization methods. As an example, Hewitt et al. (2003) used an LGM integration of an atmosphere-mixed layer ocean model to obtain their oceanic surface initial conditions for the Last Glacial Maximum. They then time integrated the AOGCM for more than 70 years, restoring the sea surface temperatures to the values obtained from the atmosphere-mixed ocean integration of the LGM climate. After the restoring period, the model was integrated normally and the simulation slowly approached a near equilibrium state. This technique resulted in the model simulation being several centuries closer to equilibrium with the LGM forcing than would have otherwise been the case. For relatively small

Fig. 7 As in Fig. 1 but for globally veraged steric sea level rise (m)



changes in radiative forcing, such as finding initial conditions for the historical twentieth century integrations, we believe our method works well. Our belief is supported by the various integrations presented here using the UVic ESCM.

In the model results shown here, switching or jumping back to 1850 conditions did not save computer time. This is once more due to the long response time scales found in the climate system. Because it is possible, but not likely, that instantaneously resetting the radiative forcing may lead to unpredictable results, we recommend that the radiative conditions be run smoothly backwards in time from present-day to 1850.

Also, based on the model results shown here, we recommend that the model be integrated for at least three centuries (longer if it can be afforded) using the 1850 radiative forcing conditions held constant. After this point, the historical integrations of the twentieth century climate can commence. If the ‘‘instantaneous switch-back’’ method is used, the model should be integrated at least four centuries using 1850 radiative forcing.

The advantages that we see using our method are as follows:

1) It provides a framework for the development of AOGCM initial conditions. This has been missing in the climate modelling community and setting a framework should help in the efforts to intercompare model results and in the understanding of their differences. Given the possible variations in our method described above, we consider this a first step toward developing a standardized method for obtain initial conditions for AOGCMs.
2) It generates internally consistent 1850 initial conditions within the framework of the model. These

Table 3 Same as Table 1 except for experiments which start from a 1998 equilibrium model climatology

	Length (years)	SAT (°C)	SST (°C)	Sea Ice (10^6 m^3)	AMO (Sv)	T 1528 m (°C)	T 5396 m (°C)	Sea level (cm)
Instantaneous switch back								
Control	148	14.01	18.22	19.68	18.21	2.528	0.821	4.90
0	148	0.22	0.17	–1.09	1.11	0.293	0.296	12.79
100	248	0.14	0.11	–0.71	0.77	0.191	0.268	8.98
200	348	0.10	0.07	–0.50	0.64	0.123	0.233	6.41
300	448	0.07	0.05	–0.30	0.51	0.079	0.197	4.68
400	548	0.04	0.03	–0.17	0.45	0.052	0.163	3.48
500	648	0.03	0.02	–0.12	0.27	0.040	0.132	2.75
Backwards Integration								
Control	148	14.01	18.22	19.68	18.21	2.528	0.821	4.90
0	296	0.14	0.10	–0.67	0.77	0.183	0.264	8.69
100	396	0.09	0.07	–0.46	0.62	0.118	0.229	6.23
200	496	0.06	0.05	–0.31	0.53	0.076	0.193	4.57
300	596	0.05	0.04	–0.22	0.42	0.050	0.161	3.40
400	696	0.03	0.02	–0.15	0.26	0.039	0.130	2.70
500	796	0.02	0.02	–0.11	0.26	0.030	0.106	2.11

Row 2 provides the value of the particular variable at year 1998 from the control experiment used in Table1. The sea level data in the last column is calculated at 1998 relative to the initial condition.

Table 4 As in Table 2 but for the experiments which start from the 1998 equilibrium model climatology

	Length (years)	SAT (°C/c.)	SST (°C/ c.)	Sea Ice (10^6 m^3 /c.)	AMO (Sv/c.)	T 1528 m (°C/c.)	T 5396 m (°C/c.)	Sea level (cm/c.)
Instantaneous switch back								
Control	148	1.06	0.78	–5.26	4.14	0.076	0.002	8.13
0	148	1.02	0.70	–5.37	–0.22	–0.003	–0.011	5.05
100	248	1.11	0.76	–4.98	–0.85	0.020	–0.018	6.12
200	348	1.19	0.79	–5.56	–0.80	0.041	–0.019	6.74
300	448	1.03	0.71	–5.40	–0.96	0.056	–0.020	7.15
400	548	1.03	0.76	–2.33	–0.22	0.063	–0.018	7.41
500	648	0.89	0.75	–1.59	4.56	0.058	–0.015	7.70
Backwards integration								
Control	148	1.06	0.78	–5.26	4.14	0.076	0.002	8.13
0	296	1.08	0.72	–3.84	–1.01	0.018	–0.018	6.21
100	396	0.87	0.72	–4.62	–1.20	0.040	–0.020	6.78
200	496	0.88	0.67	–2.93	–0.35	0.056	–0.020	7.17
300	596	1.09	0.74	–3.10	0.21	0.055	–0.017	7.39
400	696	1.20	0.78	–5.54	5.73	0.062	–0.015	7.69
500	796	1.11	0.79	–6.44	5.46	0.062	–0.012	7.77

All trends are reported as per century (/c.). Row 2 provides the trend per century of the particular variable over the years 1991–1998 from the control experiment used in Table 2.

conditions are consistent with the 1850 radiative forcing (to the extent that the model is near equilibrium at the start of the perturbation integrations).
3) It is likely to yield a fairly realistic present-day climate in the historical twentieth century integrations where the radiative conditions go from 1850 toward present day. This assumes the climate drift in the AOGCM is relatively small.

The disadvantages that we see using this method are as follows:

1) It is expensive. Using today's state-of-the-art models, integrating an additional 4 or 5 centuries is expensive and it can take several wall-clock months. However, it is common to integrate a control experiment more than 1000 model years. It is also common to integrate many ensemble members for 250 years (1850 to 2100). Since only one additional integration needs to be performed, the expense seems feasible for most groups to manage. The additional wall-clock time needed before starting the historical twentieth century integrations is remains an issue.
2) The 1850 initial conditions will vary from model to model. While this is a concern, we note that it is the case now for all current AOGCM integrations.

Our proposed method also has implications for future climate change simulations. By providing present-day initial conditions for future climate integrations and a model consistent radiation imbalance, the cold start problem is avoided (see Hasselmann et al. 1993 for more discussion on the cold start problem). The cold start problem occurs when AOGCM perturbation integrations (such as the simulation of future climate change) start from radiatively balanced conditions. Due to the large heat capacity of the oceans, it takes a while for the climate to change as the radiation is changing.

In summary, we do not view our proposed method of AOGCM initialization as the complete answer to the initialization problem. We view it as a good interim solution, waiting until better methods can be developed.

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