Spin-Up Procedures for a Coupled Climate System Model

Steven J. Phipps[1,2], Jason L. Roberts[1], Scott B. Power[4], William F. Budd[2] and Nathan L. Bindoff[1,2,3]

[1]Antarctic Climate and Ecosystems CRC, University of Tasmania, Australia (E-mail: sjphipps@utas.edu.au)
[2]Institute of Antarctic and Southern Ocean Studies, University of Tasmania, Australia
[3]CSIRO Marine Research, Hobart, Tasmania, Australia
[4]Bureau of Meteorology Research Centre, Melbourne, Australia

1. Introduction

Internal climate variability arises not only from the variability within the components of the climate system, but also from the feedbacks between them. Coupled general circulation models aim to represent both of these sources of variability. However, in order to use such models to study natural variability on decadal and longer timescales, the simulated climate should be both realistic and stable over time. In the case of the coarse-resolution models used for millennial-scale climate studies, many groups use flux adjustments in order to reduce climate drift.

Here we assess a number of different techniques for "spinning up", or initialising, a coupled general circulation model. We also investigate the relationship between the degree of realism of the control climate and the magnitude of the flux adjustments required to reduce drift.

2. Typical spin-up procedure

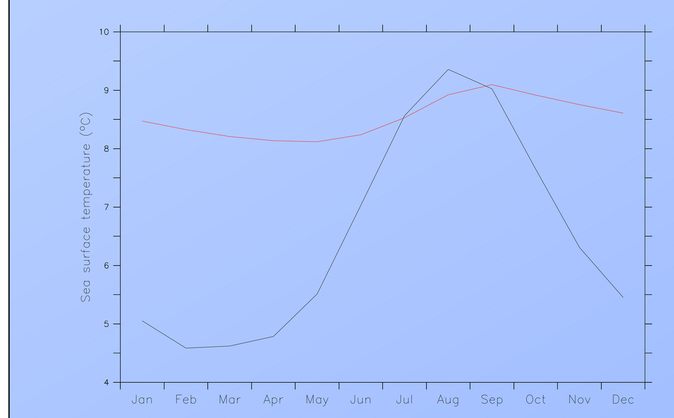

Figure 1. Climatological sea surface temperature in the region 20°–0°W, 60°–70°N. Levitus 1998 (black) and Spin-Up A (red).

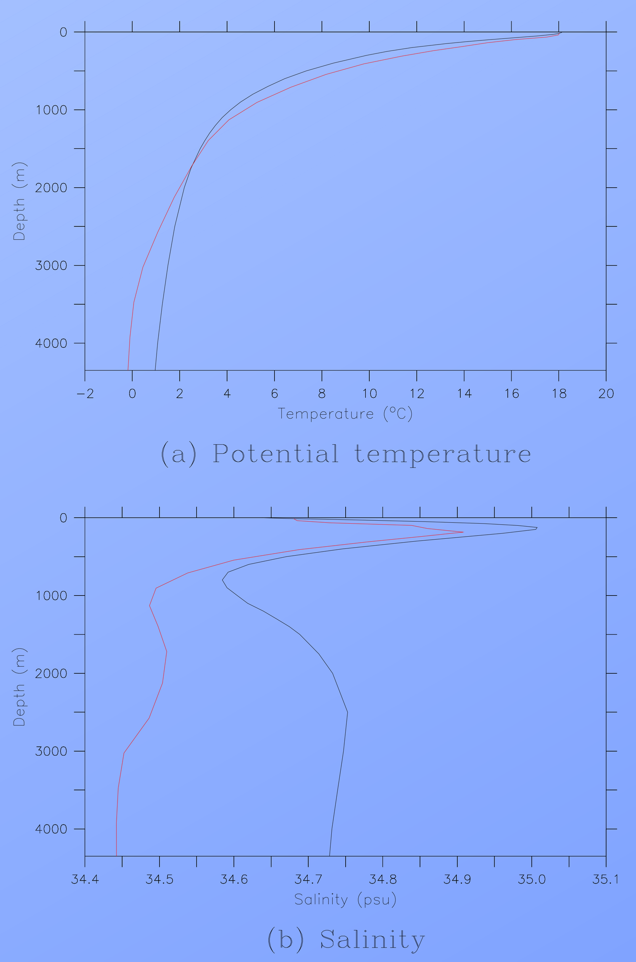

Figure 2a-b. Vertical profiles of **a** potential temperature and **b** salinity. Levitus 1998 (black) and Spin-Up A (red).

Typically, the atmospheric and oceanic components of a coupled model are spun up independently. For the atmosphere model, observed sea surface temperatures are used as the bottom boundary condition. In the case of the ocean model, observed wind stresses are applied to the ocean, while the sea surface temperature (SST) and sea surface salinity (SSS) are relaxed towards observed values. The use of a relaxation boundary condition is problematic, however, as it causes the ocean model SSTs and SSSs to exhibit both a phase lag and an attentuation of the annual cycle relative to observations.

In this study, we use the CSIRO coupled general circulation model (Gordon 2002). The horizontal resolution is R21 ($\Delta\lambda \approx 5.6^\circ$, $\Delta\phi \approx 3.2^\circ$), with 18 vertical levels in the atmosphere and 21 in the ocean. We begin by spinning up the atmosphere model (which includes a sea ice model) and ocean model independently, using the Levitus 1998 SSTs and SSSs and the NCEP2 wind stresses. The ocean model SSTs and SSSs are relaxed towards the observed values using a time constant of 20 days. We designate this experiment Spin-Up A.

Figure 1 shows the climatological annual cycle of SST in the region 20°–0°W, 60°–70°N, an area of the North Atlantic where deep downwelling takes place. Both the observed SST and the model response are shown, and the problem with the relaxation boundary condition is apparent. As well as exhibiting a considerable phase lag relative to observations, the ocean model SSTs also exhibit a strong attenuation of the annual cycle. This inhibits the formation of high-density surface water in winter and hence the formation of bottom water, with the maximum value of the meridional overturning streamfunction in the North Atlantic being just 12.1 Sv. In turn, this leads to the deep ocean being both too cold and too fresh, as can be seen from Figure 2.

A further disadvantage of spinning the model components up independently is that it can lead to the diagnosis of large flux adjustments. Any mismatch between the boundary conditions on the atmosphere and ocean models must be corrected in order to reduce drift in the coupled model. This applies to all the fields exchanged between the two models, and hence not only to the fluxes of heat, freshwater and momentum, but also to the ocean model SSTs. The flux adjustments that we diagnose from Spin-Up A are large in magnitude, as can be seen from Table 1. Not only might such large adjustments be expected to influence the modes of internal variability within the model, but they are also serving to maintain the ocean climate in its highly unrealistic state. They are therefore highly undesirable.

Experiment	Heat (Wm^{-2})	Freshwater (myr^{-1})	τ_x (Nm^{-2})	τ_y (Nm^{-2})	SST (K)
Spin-Up A	76.3	2.35	0.049	0.026	1.18
Spin-Up B	78.3	4.03	0.047	0.026	0.37
Spin-Up C	76.6	2.43	-	-	-

Table 1. Root mean square magnitudes of the flux adjustments diagnosed for the coupled model.

3. Effective boundary conditions

The ocean model SSTs and SSSs could be improved by using a shorter restoring time constant, but this results in less realistic surface fluxes. An alternative approach is to use effective sea surface temperatures and salinities, which are derived such that the model response matches observations as closely as possible.

We attempt to derive such effective SSTs and SSSs by adopting an iterative approach. Each iteration consists of spinning the ocean model up to equilibrium under the NCEP2 wind stresses and a set of effective SSTs and SSSs. We then use the response of the ocean model to derive a new set of effective SSTs and SSSs. First, we calculate the annual-mean error in the ocean model SST and SSS at each gridpoint, and subtract these errors from the effective SSTs and SSSs. Secondly, we calculate the ratio between the amplitude of the observed annual cycle and the model response, and multiply the amplitude of the annual cycle in the effective SSTs and SSSs by this amount. Beginning with the Levitus 1998 climatology as our first set of effective SSTs and SSSs, we find that a solution is reached after just nine iterations, totalling 7,000 years in duration.

However, we also need to address the phase lag which arises from the relaxation boundary condition. At each gridpoint, we calculate the Lag of Maximum Correlation, being the phase lag which maximises the correlation between the Levitus 1998 SSTs and SSSs and the model response. These lags are shown in Figure 3. The mean SST phase lag is 30 days and the values are tightly clustered around the mean, with the lag lying between 20 and 40 days over 90% of the surface of the ocean. The mean SSS phase lag is 23 days and the values are more scattered.

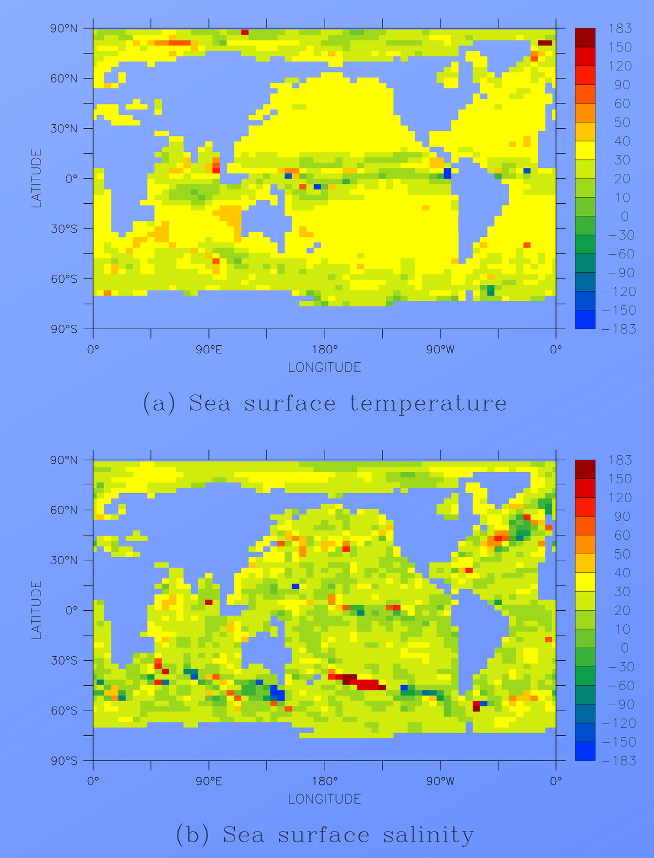

Figure 3a-b. Lags of Maximum Correlation (days) for **a** sea surface temperature and **b** sea surface salinity.

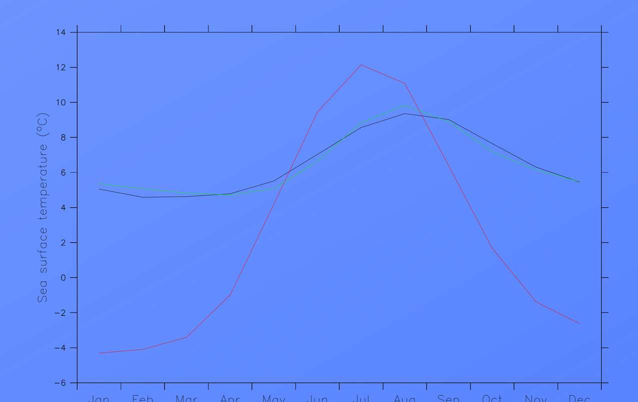

Figure 4. Climatological sea surface temperature in the region 20°–0°W, 60°–70°N. Levitus 1998 (black), effective temperature (red) and model response (green).

As the phase lags are centred around 30 days, we simply shift the final set of effective SSTs and SSSs forward in time by one month, and spin the ocean model up again. We designate this experiment Spin-Up B.

The ocean climate is found to be much more realistic than under the original boundary conditions. Figure 4 shows the effective SST that is used to force the model in the region 20°–0°W, 60°–70°N. The phase lead and considerable amplification of the annual cycle relative to observations is apparent. However, the model SST now exhibits an excellent fit to observations. The maximum value of the North Atlantic overturning streamfunction is increased to 16.2 Sv, and Figure 5 shows a large improvement in the salinity of the deep ocean, as well as a slight improvement in the temperature.

Although the ocean climate is much improved, this is achieved at the expense of a slight increase in the surface fluxes. Table 1 shows that, although smaller SST adjustments are now diagnosed, there is an increase in the freshwater flux adjustments.

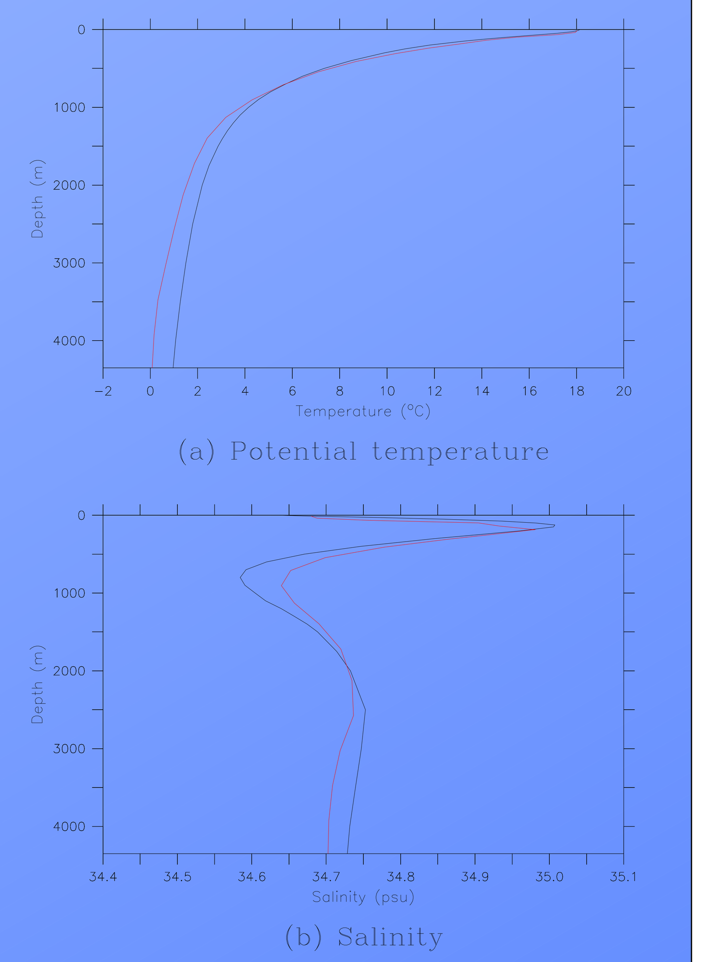

Figure 5a-b. Vertical profiles of **a** potential temperature and **b** salinity. Levitus 1998 (black) and Spin-Up B (red).

4. Dependent spin-up

By spinning the atmosphere and ocean models up together, the number of fields requiring flux adjustments in the coupled model can be reduced. We attempt this here by spinning up the ocean model using the NCEP2 wind stresses and Levitus 1998 SSTs and SSSs. The ocean model SSTs are then used to spin up the atmosphere model, and the atmosphere model wind stresses used to bring the ocean model to a fresh equilibrium. A final atmosphere model spin-up is then carried out. This approach avoids any need to apply adjustments to either the wind stresses or the SSTs in the coupled model.

We designate this experiment Spin-Up C, and find that there is little change in the ocean climate relative to Spin-Up A, although there is a slight weakening in the North Atlantic overturning to 10.9 Sv. Table 1 shows that the heat and freshwater flux adjustments are little different from Spin-Up A.

5. Conclusions

We have demonstrated that the spin-up procedure for a coupled general circulation model influences not only the control climate of the model, but also the need for flux adjustments.

Although we have shown that the relaxation boundary condition typically used to spin up an ocean model is flawed, we have demonstrated a simple yet effective modification to this technique.

By utilising a combination of the spin-up techniques assessed here, it is intended to form an ensemble of model configurations to be used for millennial-scale climate studies.

6. References

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