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Some sensitivities of a coupled ocean-atmosphere GCM

By T. STOCKDALE[1,2*], M. LATIF[2], G. BURGERS[3] and J.-O. WOLFF[2‡], [1]*ECMWF, Shinfield Park, Reading, RG2 9AX, UK,* [2]*Max-Planck-Institut für Meteorologie, Bundesstr. 55, D-20146 Hamburg, Germany, and* [3]*KNMI, Postbus 201, 3730 AE De Bilt, The Netherlands*

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ABSTRACT

A coupled ocean-atmosphere GCM is being developed for use in seasonal forecasting. As part of the development work, a number of experiments have been made to explore some of the sensitivities of the coupled model system. The overall heat balance of the tropics is found to be very sensitive to convective cloud cover. Adjusting the cloud parameterization to produce stable behaviour of the coupled model also leads to better agreement between model radiative fluxes and satellite data. A further sensitivity is seen to changes in low-level marine stratus, which is under-represented in the initial model experiments. An increase in this cloud in the coupled model produces a small improvement in both the global mean state and the phase of the east Pacific annual cycle. The computational expense of investigating such small changes is emphasized. An indication of model sensitivity to surface albedo is also presented. The sensitivity of the coupled GCM to initial conditions is investigated. The model is very sensitive, with tiny perturbations able to determine El Niño or non-El Niño conditions just six months later. This large sensitivity may be related to the relatively weak amplitude of the model ENSO cycle.

1. Introduction

The tropical ocean-atmosphere system of the earth exhibits considerable inter-annual variability, which can have a significant impact on human life and activity both in the tropics and, to some extent, in the mid-latitudes. Simple models have shown the capability for useful qualitative forecasts of a major part of interannual variability, the El Niño of the tropical Pacific (e.g., Cane et al., 1986). Work is now underway in a number of groups around the world to develop more comprehensive models that, it is hoped, may be able to produce forecasts which are both more complete and more accurate.

A global coupled ocean-atmosphere GCM is the ultimate tool for such forecasting, and such a model is being developed by a European group based at the Max-Planck-Institut in Hamburg. The ocean component is HOPE, a global model with high equatorial resolution. The atmosphere component can be either ECHAM (the Hamburg climate AGCM), or a low resolution version of the ECMWF forecast model.

The development of such a model is no easy task. The amplitude and rate of change of SST anomalies in the tropics are relatively small, of magnitude 1°C and perhaps 0.2°C per month. If these changes are to be predicted accurately, it is desirable (and perhaps necessary) that the model is able to reproduce reality to at least this accuracy. To reduce "climate drift" in a coupled GCM to below 0.1°C per month, without recourse to potentially distorting fixes such as flux correction, is a formidable task. The computational expense of the necessary numerical experimentation is a further limit on the rate at which progress can be made.

To help with the process of model development, a number of sensitivity studies with the coupled GCM have been carried out, using the ECMWF

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[*] Corresponding author.

[‡] Current affiliation: Antarctic CRC, University of Tasmania, GPO Box 252C, Hobart, Tasmania 7001, Australia.

version of the atmosphere model. These experiments have concentrated on two issues: the sensitivity of model climatology to cloud parameterizations, and the sensitivity of model integrations to initial conditions. This paper discusses the results of these sensitivity experiments, and their implications for model development and El Niño predictability. A companion paper (Latif et al., 1994) describes work with the ECHAM version of the atmosphere model, and focuses on the mean seasonal cycle and global interannual variability of the coupled system.

The remainder of the paper starts with a brief description of the model in Section 2. Section 3 details the sensitivities of the coupled model system to changes in convective cloud, stratus cloud and surface albedo. Section 4 considers a preliminary set of "identical twin" experiments which demonstrate model sensitivity to initial conditions. The paper concludes with Section 5, a summary and discussion of the results.

2. Model description

The HOPE model is a primitive equation, z-coordinate ocean GCM on an Arakawa E grid. Physical parameterizations include a 3-term horizontal viscosity, shear-dependent vertical mixing, and solar penetration below the surface. As used here, the model has a global 2.8° resolution, with the meridional resolution increased to 0.5° in the equatorial region. The polar regions of the ocean are relaxed towards Levitus (1982) climatology, since the model does not include ice. The tuning of the surface mixing physics is described in the companion paper Latif et al. (1994).

The ECMWF forecast model used in these experiments is Cycle 44, which was in operational use from October–December 1992. Relevant features of this model include: a mass flux convection scheme; a low wind speed surface flux enhancement; a multi-layer land surface with the deepest level specified from climatology; a diagnostic cloud scheme, with cloud cover and liquid water content specified according to convective activity, relative humidity, inversion strengths and other factors. The model is used only at T21 and T42 resolutions due to computational cost. The T21 version also has a change of horizontal diffusion to a more scale-selective scheme, which helps to ensure numerical stability in longer runs.

The coupling of the two models is done every ocean timestep (2 h). Fluxes of heat, momentum and fresh water are passed to the ocean, and SST is returned to the atmosphere. No flux corrections are made, and the interpolation scheme conserves heat, momentum and other integrated quantities, at least away from the coastlines. The coupled experiments all start using an ocean initial state which has been spun up using monthly mean climatological forcing, and an atmospheric initial state from the 1 January 1991 ECMWF analysis.

3. Sensitivities of the mean seasonal cycle

Prior to considering the sensitivities of the mean seasonal cycle to various factors, we will outline the main features of a typical model integration. Fig. 1 shows the ten year annual mean SST from a run of the ECMWF/HOPE coupled GCM. Several features can be noted. Tropical temperatures are everywhere too cool by about 2°C. In the Pacific, the equatorial cold tongue is too prominent, and the equatorial east–west temperature gradient is too weak. The Indian Ocean is slightly warmer than the western equatorial Pacific. In the Atlantic, the east–west temperature gradient has the wrong sign; this is associated with too-warm water off the south–west coast of Africa and a consequent weakening of the south–east trades. SSTs are generally too high in the eastern boundary regions of the subtropics. Away from the tropics, temperatures are too high in the high-latitude Southern ocean, and the Gulf stream/North Atlantic circulation is not well reproduced. SST errors in higher latitudes do not have such a large impact on the atmospheric circulation, and so initial work has concentrated on understanding the errors in the tropical regions of the globe.

3.1. Sensitivity to convective cloud cover

The first coupled integration of HOPE and the ECMWF Cycle 44 model was not a great success. The temperature of the tropics fell dramatically. Fig. 2 shows some time series plots for SST averaged over the Niño-3 area in the eastern equatorial Pacific. The standard Cycle 44 version of the model shows an almost identical steady cooling at both T21 and T42 resolutions. The rate

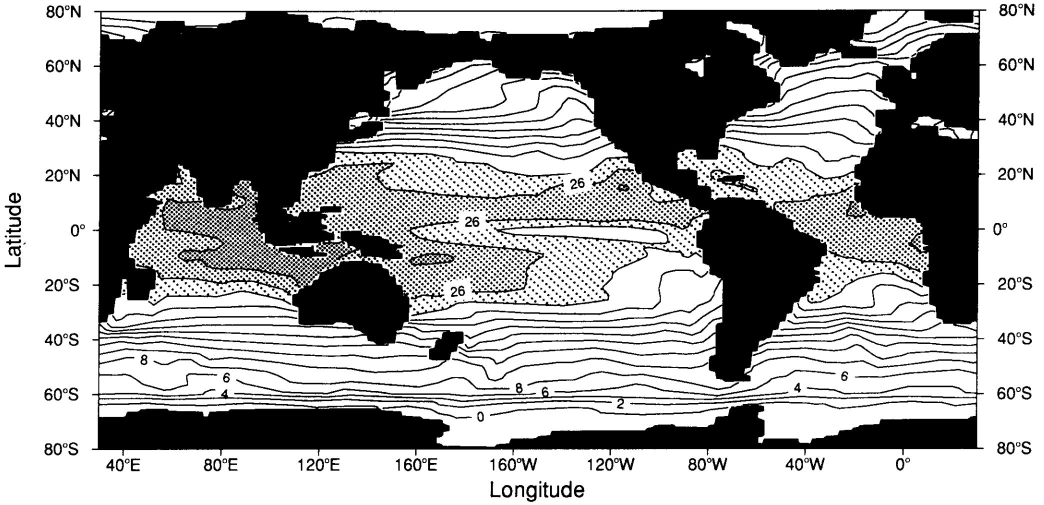

Fig. 1. Annual mean SST, calculated from the last 10 years of a 15-year run of the coupled model. Contour interval is 2°C, with shading above 24°C.

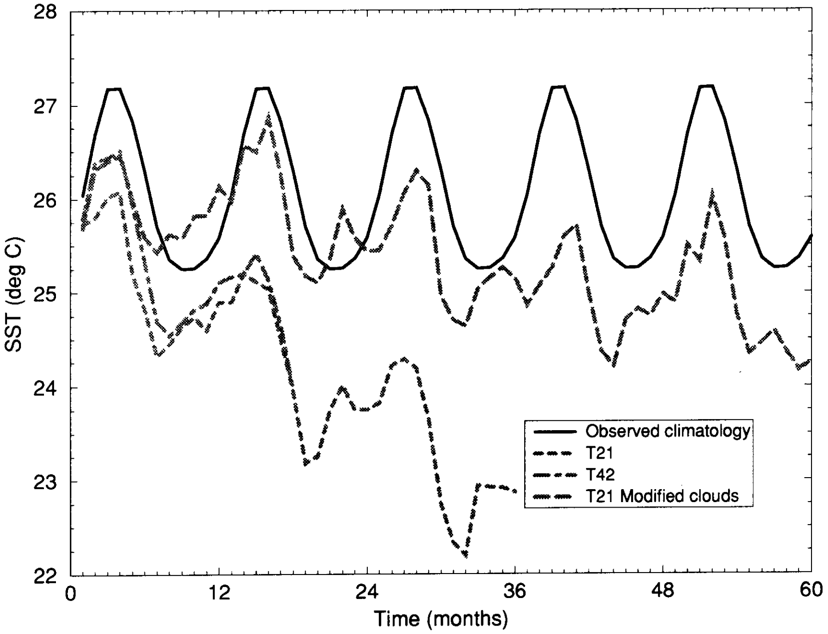

Fig. 2. Time-series plots of SST averaged over Niño-3 (5° N–5° S, 150° W–90° W). Coupled GCM runs with standard ECMWF Cycle 44 physics (T21, 36 months and T42, 18 months) are compared to an experiment with modified convective cloud cover, and to the observed mean seasonal cycle.

of this cooling (2°C in 3 years) is large even compared to the annual cycle of SST, and certainly compared to any interannual variability. A model with such a large rate of drift is not suitable for forecasting changes in the ocean-atmosphere system.

Analysis shows that although the cooling is spread fairly uniformly throughout the tropics, it is the "warm pool" regions which cool the fastest, and which end up cooling the most. This suggests that the initial cause of the tropical cooling is an error in the heat balance of the warm pool regions. A simple way of adjusting this heat balance is to change the properties of convective clouds; such clouds are concentrated over the regions of warmest tropical SST and have a large cooling effect on the surface due to reflection of solar radiation. Furthermore, the correct representation of clouds in AGCMs is known to be a difficult problem, and so a priori the cloud cover is under suspicion if a model is behaving erroneously.

The cloud cover was altered by reducing the fractional cloud coverage within a convectively active grid box from 32% to 16%. Less cloud means more solar radiation at the surface. A cloud reduction also increases the longwave cooling of the surface to space; this is a relatively small effect in the warm pool region, however, since the moist air produces an optically thick atmosphere in the longwave. Integrations of the atmosphere model with and without this change were made using prescribed seasonally varying SST. Fig. 3 shows the difference in the annual mean net surface heat flux that is produced by the cloud change. There is an increase in the net flux of more than 20 Wm^{-2} over most of the warm pool regions, and the spatial pattern of the surface flux change matches, in a rough sense, the initial cooling pattern in the first coupled model integrations.

Once the cloud reduction is introduced into the coupled GCM, the improvement is dramatic: refer back to Fig. 2, which also shows the time series of Niño-3 for the coupled model with modified clouds. Although the model still shows a slight cooling trend, this is now much smaller than the amplitude of the annual cycle, and may be small enough to allow recognition of interannual variability. An extension of this coupled model run to 15 years shows that the model reaches a quasi-equilibrium state that is about 2°C too cold in the tropics (as shown in Fig. 1). It would of course be possible to do further tuning: the cloud change described here was simply a first attempt, and it is perhaps fortuitous that the improvement was so marked. The sensitivity of the tropical temperature balance to the properties of convective clouds has been clearly established, however.

An obvious question is whether the cloud change in fact corrects an error in the model surface solar radiation, or whether it just compensates

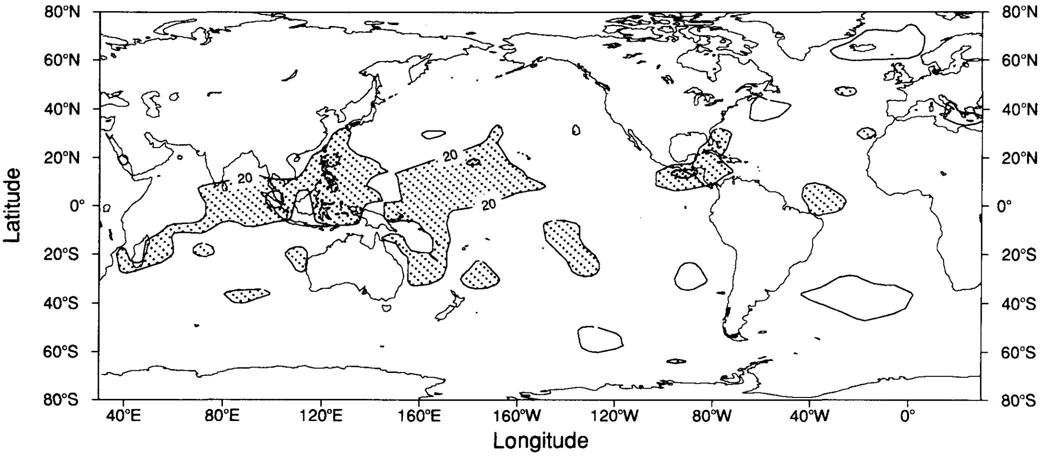

Fig. 3. Annual mean net surface heat flux difference between two 1 year runs, one using modified convective cloud cover. SSTs were prescribed in both cases. Contour interval is 20 W/m^2, with the zero contour surpressed. Shading indicates where the modified cloud cover has increased the net surface heat flux.

for errors elsewhere, such as in the latent heat component. Unfortunately, surface heat flux climatologies based on historical observations have uncertainties comparable in size to the change in heat flux we have made (see e.g., Weare et al., 1981). A useful alternative is to compare TOA (top-of-atmosphere) radiative fluxes from the model with satellite observations from Nimbus-7 and ERBE. These TOA fluxes are known more accurately than the surface fluxes, and in most circumstances any error or change in model cloud will show up in the TOA fluxes just as much as at the surface.

Fig. 4 compares TOA absorbed short-wave radiation from the prescribed SST experiments with and without the cloud modification, and satellite data from the Nimbus-7 ERB instrument. It can be seen that in the warm pool regions the original cloud scheme reflects significantly too much sunshine to space, while the modified clouds produce shortwave fluxes much closer to observations. For example, in the equatorial west Pacific the original scheme produces a net absorption of less than 280 Wm^{-2} and the modified scheme more than 300 Wm^{-2}, while the observations indicate a value approaching 320 Wm^{-2}. Incidentally, this is consistent with the fact that the coupled model still shows a slight cooling with the modified clouds: the change has not quite been large enough. Comparison of the TOA longwave fluxes with observations (not shown) tells much the same story: the coud modifications produce substantially better agreement between model and observations. The conclusion must be that the radiative effect of the cloud changes is largely correct, and that the modifications are correcting errors in the model cloud/radiative transfer interaction, and not simply compensating for errors elsewhere in the model physics. This is not to say that the specific remedy of changing the fractional cloud cover within convective gridboxes was "correct": other changes in the cloud/radiation scheme, such as a change in the liquid water content of convective clouds, would have similar though not identical results.

A final consideration is as to why the shortwave component of the atmosphere model had such a large error, or at least large compared to the other terms in the surface heat budget, as seems to be the case from this analysis. It is known that the correct representation of cloud in atmosphere models is difficult, and so it is not entirely surprising that substantial errors exist; on the other hand, the parameterizations affecting the structure of the boundary layer and hence the latent heat flux are also difficult, and it is not immediately obvious why they seem to be less in error than the solar radiative flux. The answer to this problem is that the ECMWF model has been primarily tuned for numerical weather prediction (NWP). Evaporative fluxes have a significant impact on the structure of the atmospheric boundary layer, and hence on medium-range forecasts. These aspects of model physics are thus well tuned in a properly developed NWP model. Regarding clouds, however, whether solar radiation is reflected to space or absorbed by the ocean surface has almost no direct effect on the atmosphere. Since forecasts are run with fixed SST, the net surface heat flux over the ocean is also of little concern. For NWP, therefore, the cloud/radiation interaction over oceans is not critical, and the requirement for good forecasts does not provide much of a constraint on model physics in this regard. (Cloud over land is much more important in NWP, since land temperatures are not fixed, and are quite sensitive to surface fluxes.) In conclusion, a good NWP model can be expected to have most of its physics well tuned by the requirement for good forecasts; the cloud field over the oceans should be treated with caution by coupled modellers, however.

3.2. Sensitivity to boundary layer cloud

Even with the correct overall temperature balance for the tropics, there are still likely to be local problems. One of these is excess temperatures in the eastern boundary regions of the sub-tropical oceans, the worst case being off the coast of Namibia. Analysis of the coupled run shows an almost complete absence of low level inversion cloud in these regions (Fig. 5a). The tendency to underestimate inversion cloud over the sub-tropical oceans is a known weakness in a number of AGCMs.

In the ECMWF model, low level stratus cloud is diagnosed according to the strength of the boundary layer inversion and the relative humidity. Experiments show that the lack of cloud over the appropriate regions of the sub-tropical oceans is due to insufficient relative humidity: the inversion is still strong, but almost no cloud is diagnosed because the boundary layer air is not sufficiently

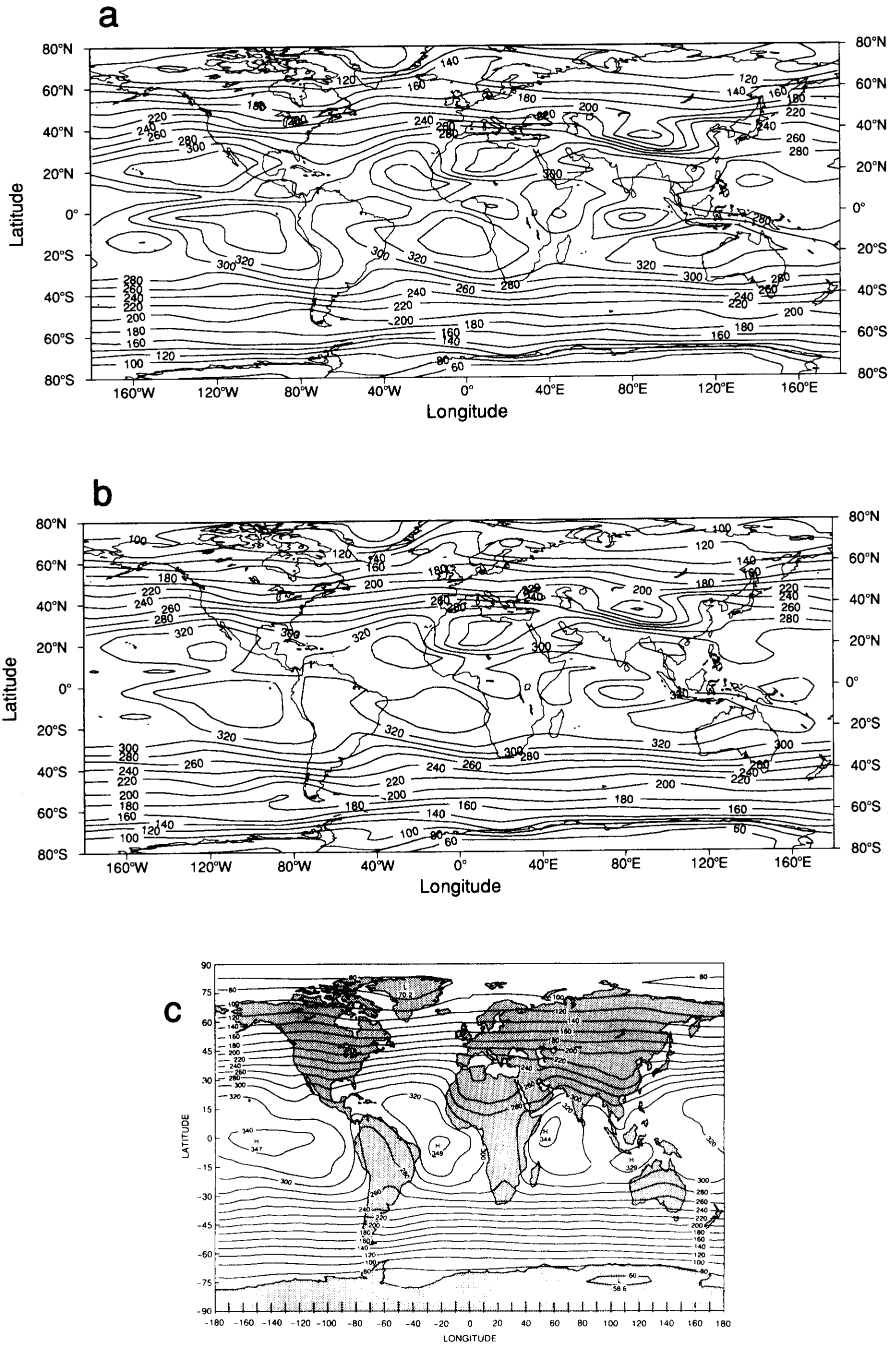

Fig. 4. Comparison of TOA solar fluxes with satellite observations. Modified cloud cover gives better agreement over warm pool regions. Contour interval is 20 W/m^2. (a) Annual mean flux with standard cloud cover and prescribed SST. (b) Annual mean flux with reduced convective cloud and prescribed SST. (c) Nimbus-7 ERB annual mean flux, 1979–87 average. From Ardunay et al. (1992).

moist. Now it may be that the overall physics of the model produce air that is slightly too dry, or it may be that the diagnosis scheme is wrong in saying that air of this humidity cannot form inversion stratus cloud. Changing the vertical structure and moisture properties of the model in a specified direction is a difficult job, best left to the experts. Changing the diagnostic rule for the clouds is straightforward, however, and allows model sensitivity to cloud changes to be assessed. Thus an experiment was undertaken in which the humidity constraint on inversion cloud was relaxed considerably. This causes problems in other regions (particularly over land in high latitudes), and is probably not the ideal solution to the problem of insufficient cloud cover over the sub-tropical oceans. Nonetheless, a change of this sort allows an easy assessment of the sensitivity of the coupled system to boundary layer cloud.

A four year integration of the coupled model with the inversion cloud adjustment was made. Inversion cloud over the low latitude oceans was

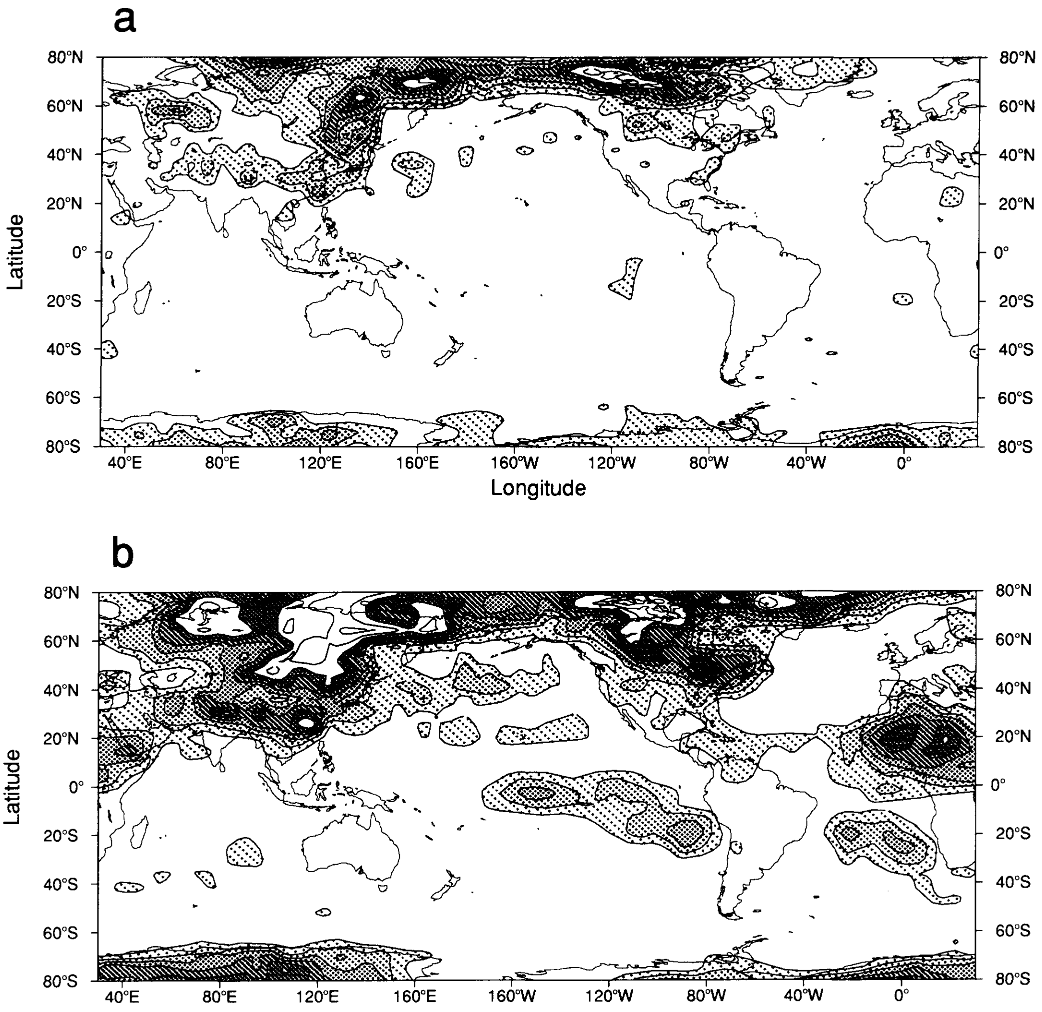

Fig. 5. Boundary layer inversion cloud in the coupled GCM. Monthly mean inversion cloud cover for January of year 4. Contour interval is 10%, cloud cover above 10% is shaded. (a) Standard case. (b) Adjusted to give more inversion cloud.

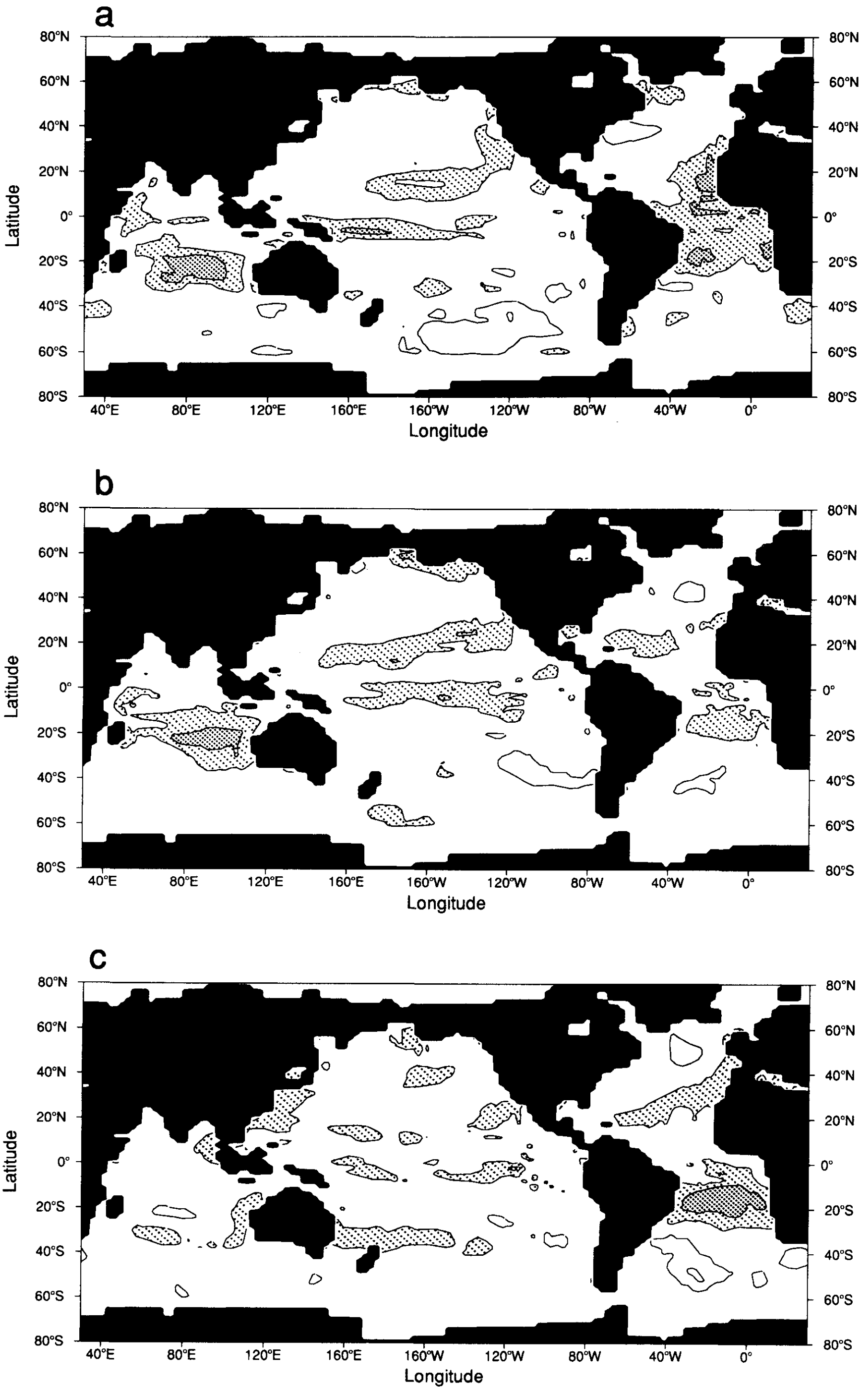

Fig. 6. Surface temperature change produced by an increase in inversion cloud. Contour interval is 1 °C, with the zero contour surpressed and areas of cooling shaded. (a) After 2 years, (b) after 3 years, (c) after 4 years.

significantly increased, from 5% to 35% over the south-eastern tropical Pacific, and from 10% to 35% over the south-eastern tropical Atlantic (Fig. 5). Note that inversion cloud cover of 35% is still less than observed values, which are in excess of 50% (Hartmann et al., 1992). The increase in stratus cloud produces a small but significant reduction in the net surface radiation, typically 10–15 $\mathrm{Wm^{-2}}$ in the annual mean; this is about $\frac{2}{3}$ of the reduction in the surface solar radiation.

The temperature change in the coupled model caused by this radiative perturbation is small but definite, with an average cooling of perhaps 1 °C in response to the 10–15 $\mathrm{Wm^{-2}}$ forcing. This cooling is not enough to remove the local warm bias in the model, and even a more realistic increase in cloud cover might not be sufficient if a simple extrapolation of these results applied. Nonetheless, a significant improvement in the model mean state has been made, and the model sensitivity to boundary layer cloud demonstrated.

One difficulty in assessing the temperature change is the natural interannual variability of the model. Fig. 6 shows the difference in SST between the experiments with and without the inversion cloud at the end of 2, 3 and 4 years. It is immediately apparent that the average cooling of the inversion cloud regions is of a similar magnitude to the variability of the model SST. The model to model SST "anomalies" have a persistence timescale of several months, and so to average out the effects of the natural variability it is necessary to run both models for several years. Multi-year runs are thus necessary for investigating both equatorial dynamics and mid-latitude fluxes. Detailed tuning of a coupled GCM will be very expensive computationally.

A final effect of the inversion cloud change is also worth noting. Fig. 7 shows the time series of Niño-3 from the coupled runs with and without the inversion cloud. The inversion cloud seems to produce a significant change in the model annual cycle: the spring warming is unchanged, but the cooling in the second part of the year is significantly stronger. When assessed over a 15-year period, the standard model run (i.e., without increased inversion cloud) has a reasonable annual cycle of Niño-3, but still suffers slightly from a

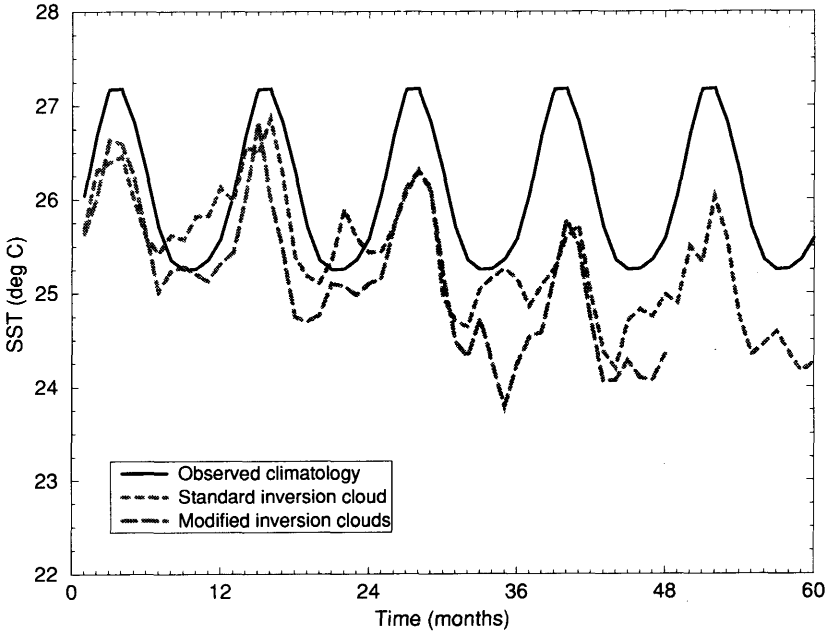

Fig. 7. Effect of the inversion cloud change on the seasonal cycle of Niño-3 SST. Increased inversion cloud gives a stronger, more pronounced annual cycle.

spurious warming in the second part of the year. It may well be that an extended integration with a better representation of inversion cloud would avoid this problem.

3.3. Sensitivity to surface albedo

We have not yet undertaken a systematic study of the sensitivity of the coupled model to surface albedo. Nonetheless, some tantalizing results are available from a set of experiments originally designed to investigate small perturbations in initial conditions. In fact, these five one year integrations were made using a surface albedo climatology different from that used by the corresponding control integrations. Fig. 8 shows the two albedo fields over the Amazon region: the "old" albedo is that used in the control experiments (and all other experiments described in this paper), while the "new" albedo is used in the set of 5 integrations discussed here.

If the evolution of Niño-3 in these five experiments is compared to the set of control integrations, a clear and consistent difference is seen, substantially above the noise level caused by the small initial perturbations. Fig. 9 shows a comparison between a mean "annual cycle" constructed from these five experiments and the mean annual cycle of the control runs. The difference is large, with the new albedo seeming to cause a weaker annual and stronger semi-annual cycle. Of course, a set of 5, 1-year integrations is not the same as 1, 5-year integration, and the "annual cycle" shown here is not the same as would be produced by a long run with the new albedo.

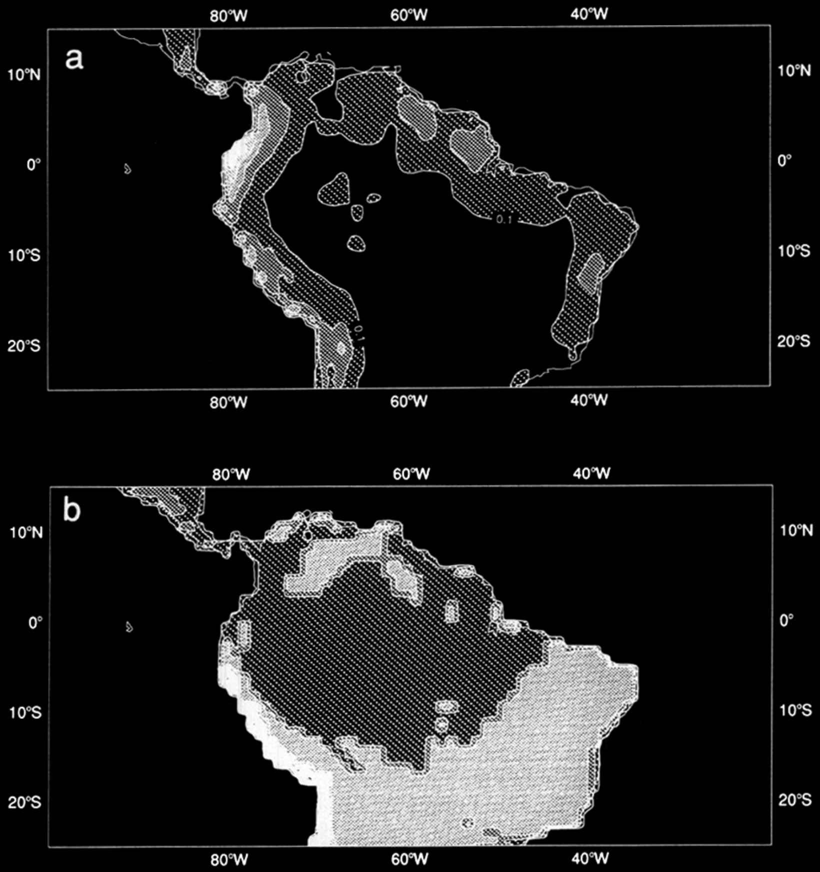

Fig. 8. Model albedo fields over the Amazon. Contour interval is 0.04, shading above 0.10. (a) Old albedo. (b) New albedo.

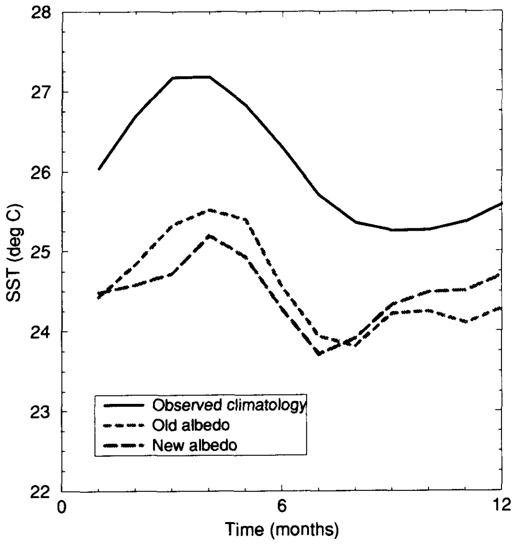

Fig. 9. Effect of the albedo change on the Niño-3 SST mean seasonal cycle. The seasonal cycle for the new albedo is constructed from five 1 year runs, and is not a true mean cycle.

Nonetheless, the new albedo has a substantial impact on the coupled model. It is interesting to note that changing to an albedo field much closer to that used by ECHAM (at least over the Amazon) looks as it it may produce an annual cycle much closer to that of the ECHAM/HOPE coupled system (Latif et al., 1994), although a longer integration would be needed to see if this is in fact the case.

4. Sensitivity to initial conditions: predictability experiments

The coupled GCM produces interannual variability somewhat similar to that in the ECHAM/HOPE model running at Hamburg, and analyzed in Latif et al. (1994). The ECMWF/HOPE variability is fairly realistic as regards the temporal/spatial patterns of SST anomaly development, but the amplitude of the ENSO-related SST anomalies is too small. The last 10 years of the model integration have a standard

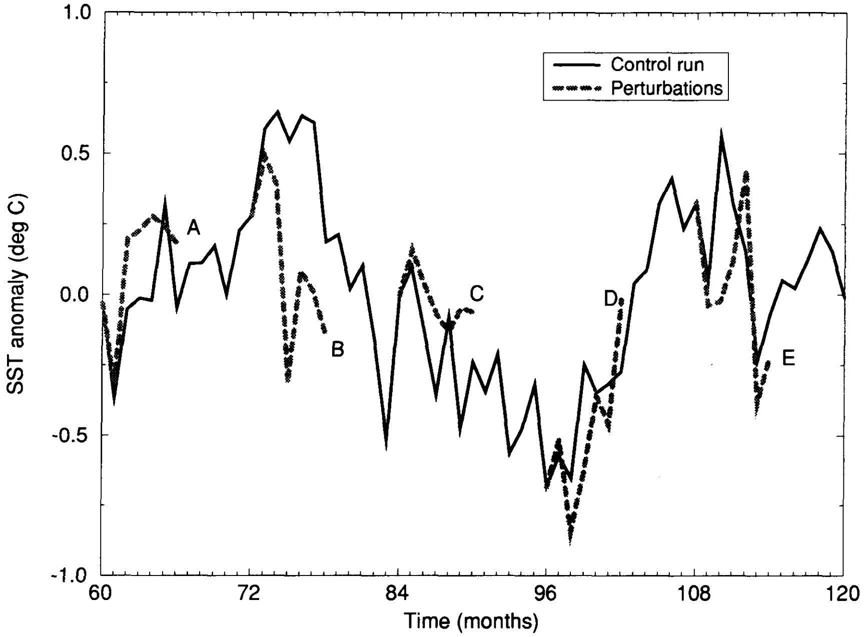

Fig. 10. Time-series of Niño-3 SST anomalies for the "identical twin" experiments. The continuous line is the control run of the model; the five dashed lines are the perturbed integrations.

deviation in Niño-3 SST anomalies of only 0.3°C, and overall the amplitude of variability seems to be too weak by a factor of 2–3.

It can be very useful to have some idea of the sensitivity of a model to initial conditions, in part to give guidance in future experimental design. A study of model sensitivity to initial conditions is equivalent to determining model predictability: high sensitivity means that the system cannot be well predicted even if the initial state is known rather accurately. Several studies on coupled model predictability have been made (e.g., Goswami and Shukla, 1991), but have used simpler models. A coupled GCM might be expected to have a lower limit of predictability, because it includes many sources of atmospheric "noise" missing from simpler models.

The basic idea of the experiment is to take a period from the freely running (and interannually varying) coupled GCM, and to spawn a number of "identical twin" experiments from the original integration. The original integration forms the control: each twin experiment starts at a different time with initial conditions almost, but not quite, identical to that of the control run at the starting point. The average divergence of the twin experiments from the control integration gives a measure of the predictability of the coupled system.

Due to the computational expense and the preliminary nature of the study, only five "twin" experiments were made. In each case, the perturbation is very small: the ocean initial conditions are identical, and the atmosphere initial conditions differ only in a numerical truncation to 24 or 16 bits and a forward timestep. Plots of 850 hPa wind difference after 3 days show no difference above 0.5 m/s in the mid-latitudes, and only small differences in the tropics associated with the switching on or off of convection. After 30 days, however, the atmospheric flows become almost entirely decorrelated. The small initial perturbation means that this is a highly idealized experiment which gives the upper bound to the model predictability.

Fig. 10 shows the results from the control and perturbed experiments as illustrated by Niño-3 SST anomalies. It will be noted that after one

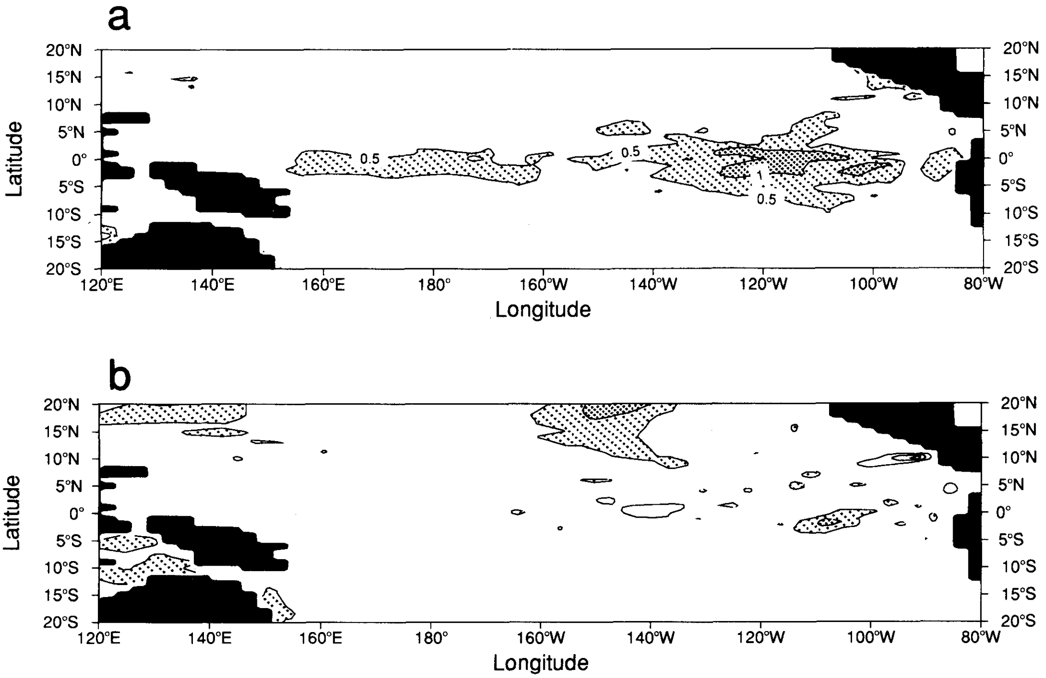

Fig. 11. A comparison of SST fields for perturbation run "B" and the control run, 5 months after the perturbation. Contour interval is 0.5°C, with zero surpressed and positive anomalies shaded. (a) Control run. A substantial El Niño in progress. (b) Perturbed run. Near normal conditions.

month, the SST differences are still very small; this is because the atmosphere takes almost this long to become decorrelated. Thereafter, however, the month-to-month differences in SST can be appreciable. This is consistent with a significant stochastic component to the monthly variations in Niño-3. What is striking, however, is that although in some cases the overall agreement in the six month period is good (e.g., case D), in one case it is really very bad (case B). Fig. 11 shows the actual plot of SST for this case after five months. The control run produces a significant warm event; the identical twin does not. In other words, the difference between El Niño or non El Niño can, at least sometimes, be determined by the tiniest of atmospheric perturbations just five months earlier.

5. Conclusions

We have presented here a number of sensitivities of a coupled ocean ocean-atmosphere GCM. The model is sensitive to the parameters controlling various types of cloud cover and to the surface albedo. The model interannual variability is strongly sensitive to initial conditions. There are of course many other processes and parameterizations to which the model will be sensitive, and for the most part these have not been investigated by us (although see Latif et al., 1994 for sensitivities to ocean surface mixing).

Cloud sensitivity is the most important process that we have looked at, perhaps for several reasons. Clouds can be difficult to get right in atmosphere models, and observational data is often good enough to tell you that the model is definitely wrong. Clouds also have a big impact on the surface radiative budget, and thus on SST in a coupled model. If an NWP model is being adapted for use in a coupled GCM, this large impact may not have been well tuned. Finally, if a model uses diagnostic cloud schemes, then the cloud properties can easily be adjusted, an ideal situation for sensitivity studies and model tuning.

A further comment concerning clouds is the difference in model sensitivity to local and global changes in cloud cover. In the case of changing convective cloud cover, which affected almost the whole of the tropics, the temperature sensitivity of the coupled system to radiative forcing can be estimated as less than or equal to 5 Wm^{-2} per 1 °C change. In the case of the more localized inversion cloud change, the sensitivity is in the range 10–15 Wm^{-2} per °C. This is not surprising, since a global change in shortwave forcing can only be balanced by a change in longwave radiation to space, which may require quite large surface temperature changes due to the greenhouse effect; a local change can be balanced by heat exchange with other parts of the globe. The difference between local and global sensitivity has consequences for model tuning. Because the global balance is very sensitive, it is more difficult to get right; on the other hand, it can also be tuned much more precisely. Local errors may not look so serious to start with, in that the temperature effects are less dramatic; but to eradicate the errors altogether may be more difficult because they are less sensitive to model changes.

One aspect of the model simulation that has been given attention is the annual cycle in the eastern Pacific. The experiments reported here reveal two sensitivities of this annual cycle: to low level stratus cloud in the south east Pacific, and to land surface conditions over the Amazon. A lack of inversion cloud can create a more semi-annual cycle, as can an increase in surface albedo over the Amazon. It is likely that changes/improvements in other aspects of the land surface parameterization would also have an impact.

As to predictability, it seems that the coupled GCM is too sensitive to atmospheric perturbations. This may be because of the relatively weak amplitude of the model ENSO cycle: a weak oscillating signal will be more vulnerable to disruption by noise than a strong oscillating signal. Indeed, the mechanism of interannual variability within the model may not be correct: the model seems to act more like a stochastically forced near-resonant system than a non-linear oscillator. The predictability of the coupled GCM is therefore probably lower than that of the real atmosphere ocean system. Nonetheless, these results are a reminder that atmospheric noise may at times play an important role in determining the future evolution of the system. Much more work on the predictability of ENSO is needed.

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