PCMDI

Program for Climate Model Diagnosis and Intercomparison

UCRL-JC-131633

PCMDI Report No. 46

The Sensitivity of AGCM Simulations to the Temporal Resolution of Ocean Surface Boundary Conditions

by

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September 1998

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TABLE OF CONTENTS

Abstract

Climate simulation experiments involving atmospheric general circulation models (AGCMs) are routinely forced with prescribed ocean surface boundary conditions. For instance, in the standard experiments of the Atmospheric Model Intercomparison Project (AMIP), sea surface temperature (SST) and sea ice fraction are defined in terms of the monthly averages of an observed data set. Although this is the traditional approach for AGCM simulations, higher frequency averages of this surface forcing are now available. In this study, we investigate the statistically significant differences in a simulated climate by performing two ensembles of AGCM integrations with the surface forcing defined by different averaging periods. We construct two surface forcing data sets of daily SST and sea ice fraction from the same set of observations. The first data set is obtained by linearly interpolating between the mid-points of observed weekly means; the second is similarly obtained, but from observed monthly mean values. The largest differences in the two reconstructions of daily SST are found in places and seasons where the temporal variability is largest. Over broad areas of the mid-latitude ocean, the daily forcing data derived from monthly means fail to capture the sharp summertime maxima found in the forcing series based on weekly mean data. In addition, some evolving structures with time scales less than one month in the tropical oceans cannot be well reproduced by the monthly mean data. For sea ice, the differences are found mostly at the ice margins during months of rapid change in ice coverage.

The impact of the different temporal specifications of surface boundary conditions on the simulated climate is assessed in relation to observational uncertainty and model errors. Two ensembles were generated with a version of the LLNL AGCM, each comprising 18 simulations, one forced by the boundary conditions based on weekly data, and the other by the monthly data. Grid-point t-tests were then used to examine the statistical significance of differences in the ensemble means of various quantities. For variables such as atmospheric boundary layer temperature, surface pressure and latent heat flux, the overall differences in the "weekly versus monthly" ensemble means were judged to be statistically significant (under the assumption that at least 5% of the total number of grid-points were statistically independent). However, differences in ensemble means were still smaller than the observational errors in the most skillful of current models. Moreover, for many variables, the differences between the two ensemble means were smaller than estimates of uncertainties in the observations themselves. Thus, given the current observational uncertainty and model errors, we conclude that for AMIP-like simulations it is sufficient to prescribe SST and sea ice fraction with monthly resolution.

1 Introduction

Atmospheric general circulation models (AGCMs) are often forced with observational estimates of sea surface temperature and sea ice extent. Traditionally, this forcing has been based on monthly averages of the observations. Typically, it is assumed that monthly average sea surface temperatures (SSTs) and sea ice extent represent mid-month values that are then interpolated to the daily values used to force AGCMs. Regardless of the interpolation method used, the variability of the actual SSTs or sea ice extent cannot be realistically captured on time scales of less than one month. The question arises as to whether forcing AGCMs with boundary conditions based on higher frequency observational data sets could alter the simulated climate enough to be of practical importance in assessments of model skill.

This issue is highly relevant to the Atmospheric Model Intercomparison Project (AMIP; Gates 1992), which is attempting to evaluate AGCMs based on a standard experiment in which the SST and sea ice fraction have been prescribed. In the first phase of AMIP, thirty-two AGCMs simulated the climate of the decade 1979-1988 with boundary conditions prescribed from satellite-derived and *in situ* measurements of monthly mean SSTs and sea ice distribution (Gates, 1995). The second phase of AMIP (Gleckler, 1996) involves a longer time series of surface boundary conditions (the 17 years spanning 1979-1995). For part of this period time series of weekly average boundary conditions are now available. The Optimal Interpolation SST data set (OISST; Reynolds 1994), for example, contains weekly values of SSTs from December 1981 to present. Weekly values of sea ice fraction are also available, e.g. from Nomura (1995) for the period December 1978 to November 1991, and from Grumbine (1996) for November 1991 to present. Thus it is possible to test whether the simulated climate is significantly affected by forcing AGCMs with surface conditions that include variability at a higher frequency than the monthly mean values traditionally prescribed.

The structure of this paper is as follows. In Section 2, we compare two surface boundary condition data sets, one based on weekly mean observations, and the other based on monthly mean observations (computed from the weekly means). In Section 3, we present a case study in which an AGCM is forced by daily boundary conditions based on weekly means in one case and on monthly means in the other. By performing 18 realizations with each set of forcing data, we are able to assess whether there are locally significant differences in the mean climate responses to the weekly and monthly forcings. Section 4 considers the larger question of whether such differences are large relative to current model errors and observational uncertainty. The implications of this study are summarized in Section 5.

2 Comparison of weekly and monthly boundary condition data

The SSTs used in this study were originated from the daily Optimal Interpolation Sea Surface Temperatures (OISST, Reynolds 1994) constructed at the National Centers for

Environmental Prediction (NCEP). Reanalyzed weekly mean blended satellite and in situ data (Kalnay *et al*., 1996) were further processed (Fiorino, 1997) to insure consistency with the sea ice concentration data (see below). The horizontal resolution is one degree in longitude and latitude ($1^o \times 1^o$).

The sea ice concentration (percentage area covered by ice) was taken from Nomura (1995). The data set was constructed with passive microwave observations from the SMMR (Scanning Multichannel Microwave Radiometer) and SSM/I (Special Sensor Microwave Imager) instruments aboard the Nimbus-7 and DMSP satellites. An algorithm developed by Cavalieri *et al*. (1992) was used to convert the passive microwave measurements into sea ice concentration on a $1^o \times 1^o$ grid.

From the daily values of the observational data sets, we have computed weekly and monthly means. The monthly means are taken to be mid-month values and are then interpolated linearly to daily values. Similarly the weekly values are taken to be mid-week values and linearly interpolated to daily values. This yields two sets of daily SSTs and sea ice cover, with the first a more faithful representation of the variability on sub-monthly time scales. Forcing data sets were constructed at two horizontal resolutions: the original $1^o \times 1^o$ resolution and a coarser $5^o \times 4^o$ resolution (5^o in longitude and 4^o in latitude) more typical of that used in many current AGCM applications.

2.1 Sea surface temperature comparison

The two data sets of daily boundary conditions (one derived from monthly means and the other from weekly means) are compared by computing their temporal root-mean-square (RMS) differences at each grid point over different intervals. Fig. 1a shows the RMS difference between the two SST daily time series for one selected month (August 1987) at a horizontal resolution of $1^o \times 1^o$. The largest differences (> 0.7^oC) are found in northern mid-latitude oceans. In the winter hemisphere and in the equatorial oceans the differences are generally small with the exception of the eastern equatorial Pacific, where there is a narrow equatorial band with RMS differences between 0.3^oC and 0.6^oC.

For comparison, the same map is shown in Fig. 1b but with sea surface temperatures interpolated to the coarser $5^o \times 4^o$ horizontal resolution of the AGCM used here (see Section 3.1). A smoothed version of the same spatial structures is seen in the coarser resolution case; note that the narrow band of large RMS differences in the eastern equatorial Pacific is much less distinct at the lower resolution.

The difference between the two SST data sets is strongly dependent on season. This is illustrated in Fig. 2, which also shows weekly versus monthly RMS differences, but now as a function of time (i.e., month) and in the form of zonal means over the global ocean. Results are displayed using monthly-mean data over five annual cycles (1983-1987). There is a pronounced seasonal cycle, with largest RMS differences in the respective summers of the two hemispheres, peaking in August (Fig. 1) over the northern oceans. Figs 3a-c show the interpolated weekly and monthly SST time series at three selected grid points on the $5^o \times 4^o$ model grid. Examination of these plots indicates that the differences shown in Figs 1 and 2 are due primarily to two factors: 1) the monthly averages underestimate the actual values of the August maxima (see e.g., the north Atlantic in Fig. 3a); 2) the interpolated monthly data miss some components of the sub-monthly time scale variability (see, e.g., Figs. 3b,c). Both interpolation methods capture most of the interannual variability.

2.2 Sea ice

Figure 4a (4b) shows the RMS differences between the daily Arctic (Antarctic) sea ice concentrations derived from interpolated monthly and weekly values for August 1987 at 1^{o} x 1^{o} resolution. The ice concentration is the fraction of the surface covered by ice. At the sea ice margins, where the ice concentration varies most rapidly, the RMS differences are often large, sometimes exceeding 10%. Similar differences are found for other months where there is rapid seasonal transition in the ice coverage.

Many AGCMs do not account for fractional sea ice, but instead each grid cell is assumed to be either ice-free or completely ice covered. In these models sea ice “masks” (with each location either ice-free or completely ice-covered) must be specified for each month. The ice masks are usually determined by analysing observations of sea ice concentration. A mask cell is assumed to be completely ice covered when the observed concentration is greater than a specified threshold (e.g., 50%), and ice-free otherwise. When the RMS difference for the two daily masks is calculated at the AGCM resolution, it exhibits differences at the sea ice margins that can be larger than in the case of fractional sea ice.

3 Comparison of simulated climates

The primary question addressed by this study is whether or not a modification in the temporal resolution of the surface boundary conditions can significantly change the mean state or other features of importance in the climate simulated by an AGCM. In order to address this question, we present a case study in which an AGCM is used to perform two ensembles of simulations forced by the higher and lower temporal resolution surface boundary conditions described in Section 2.

3.1 Description of the AGCM

The atmospheric general circulation model used in this study is a recently adapted version of the UCLA model (University of California at Los Angeles) explicitly designed for distributed memory massively parallel computers (Wehner *et al*., 1995).

The model formulation is essentially the same as that used in the experiments carried out under the protocol of the first phase of AMIP (Phillips 1994). The dynamics of the atmosphere are simulated via a finite difference technique on the Arakawa C-mesh (Arakawa and Lamb, 1977 and 1981). The horizontal resolution is 5^{o} longitude x 4^{o} latitude. The model has fifteen vertical layers with a model top layer at 1.0 mb (Arakawa and Suarez 1983). The planetary boundary layer is assumed to be well-mixed and is represented by a single layer, the height of which is computed. Sub-grid scale parameterizations include a layer cloud instability calculation at the top of the planetary boundary layer, moist convective instability adjustment, surface fluxes of momentum, moisture and energy (Suarez *et al*., 1983), cumulus convective transport of energy, momentum and moisture (Arakawa and Schubert, 1974), infrared radiation transport (Harshvardan *et al*., 1987), shortwave (visible and UV) radiation transport (Katayama, 1972), gravity wave drag (Kim and Arakawa, 1995) and the evolution of ground temperature and snow cover (Arakawa, 1972). The climatology of the model exhibits a systematic cold and dry bias as is common among models of this level of sophistication (Wehner and Covey, 1995).

3.2 Ensemble calculations

We used the model described in Section 3.1 to perform two ensembles of atmospheric simulations. In one ensemble, designated ensemble *M* (for monthly), the model is forced with daily surface boundary conditions interpolated from monthly means. In ensemble *W* (for weekly), the forcing is by daily surface conditions interpolated from weekly means. The sole difference between the two sets of simulations is in the boundary conditions of SST and sea ice concentration.

Each of the two ensembles contains eighteen realizations of fifteen months duration. The first three months of each realization were discarded (to eliminate the effects of initial state similarity), leaving one annual cycle per realization, each starting in January 1987 after a 3 month spin-up period. The initial conditions for each realization of the ensembles were obtained from a separate simulation. Data at 12 noon GMT from the last 18 days (a different day for each realization) of October in that simulation were used for the initial conditions. Each initial state is used to generate a matched pair of simulations, one forced by ensemble *M* boundary conditions, the other by ensemble *W* boundary conditions.

The daily values of SST were linearly interpolated from the monthly or weekly means, as described in Section 2. Sea ice was treated in a slightly different way. First, the monthly and weekly mean time series were transformed into two sets of sea ice/open ocean masks by testing if the concentrations in the original data sets were greater or less than 50%. Then, in the case of monthly means, when the sea ice cover between two consecutive months changes from open ocean to frozen, the sea ice thickness is increased linearly from 0 up to 3 meters from the first mid-month to the following one. Thus the AGCM grid cell freezes on the 15th day of the month following the first monthly value that is more than 50% ice covered. A similar treatment is applied when sea ice melts. As a consequence, grid cells in the model are completely covered by sea ice during longer periods than they would have been had we linearly interpolated observed sea ice concentration and then generated a daily sea ice/open ocean mask based on a 50% threshold. In the case of weekly means the procedure is the same, but with appropriate changes to accommodate the higher frequency data.

3.3 Results

To identify regions where (for some specified climate property) the differences in the ensemble means *W* and *M* are large relative to the pooled between-realization variability in each ensemble, we performed a Student's *t*-test at each grid point:

where the pooled between-realization variance, σ_P^2, is given by

$$t(x) = \frac{\overline{W}(x) - \overline{M}(x)}{\sigma_P(x)\sqrt{1/N_W + 1/N_M}}$$

$$\sigma_P^2(x) = \frac{(N_W - 1)\sigma_W^2(x) + (N_M - 1)\sigma_M^2(x)}{N_W + N_M - 2}$$

and the between-realization variance of ensemble W, $\sigma_W^2(x)$ is

$$\sigma_W^2(x) = \sum_{i=1}^{N_W} \left[W_i(x) - \overline{W}(x) \right]^2 / (N_W - 1)$$

Here $\overline{W}(x)$ and $\overline{M}(x)$ are the ensemble means for some specified property of the simulation (e.g., the monthly-mean ensemble-mean temperatures in May 1987 in Fig. 5a), each computed with 18 realizations (N_W , N_M=18). The index i runs over the number of realizations while the index x runs over the spatial dimension (number of grid-points). We next calculate a local probability, $p(x)$, and compare this with stipulated local significance thresholds of $\alpha_1 = 0.05$ and $\alpha_2 = 0.1$. Finally, we determine the number of grid cells with local $p(x)$ values exceeding the 10% and 5% significance thresholds, and convert these to fractions of the total number of model grid points (Table 1). Since the variance we consider is that between uncorrelated realizations of the same experiment, we do not need to account for temporal autocorrelation effects in the *t*-tests.

3.3.1 Planetary boundary layer temperature

In the model used in this study, the temperature at mid-pressure level in the planetary boundary layer is a measure of the near-surface air temperature. The height of the pressure level is not constant but is computed by the model, typically ranging between 50 and 500 m. The boundary layer temperature is a model prognostic variable that is expected to be sensitive to differences in the surface boundary conditions. In fact, it is the variable with the largest fraction of grid points with statistically significant differences in ensemble means (see Table 1).

The difference between the boundary layer temperature averaged over the two ensembles (mean of ensemble *M* minus mean of ensemble *W*) is generally small (< $\pm 0.5^{o}$C) over the open ocean, as is evident in Figs. 5a and 6a for the selected months May and August 1987. The local probability $p(x)$ that the ensemble means $\overline{W}(x)$ and $\overline{M}(x)$ are drawn from the same population is shown for these two months in Figs. 5b and 6b, respectively. In May 1987, the differences between the two ensemble means are statistically significant in a number of separate regions, e.g., south of the Hudson Bay, in the Indian Ocean, and at the Antarctic sea ice margin. Areas with differences in $\overline{W}(x)$ and $\overline{M}(x)$ that are significant at the 10% level or higher cover 22.7% of the total surface area.

In August 1987, the fractional area with significant differences in ensemble means increases to 29.5%. Two coherent areas with significant differences are evident in the northern oceans, corresponding to areas where the RMS differences for the SST in August are maximum (Fig. 1).

The May 1987 results indicate that in the region south of the Hudson Bay, ensemble *M* is colder than ensemble *W* by about 1^{o}C, a result that is locally significant at the 95% level or better (Figs. 5a,b). A comparison of each of the "matched pairs" of simulations (a matched pair comprising the simulations of ensemble *M* and ensemble *W* that have the same initial conditions) reveals that only nine out of the eighteen pairs exhibit a colder ensemble *M* result in the area south of the Hudson Bay. This result is apparently unrelated to ice coverage differences in the Hudson Bay in May 1987. In contrast, in areas yielding statistically significant differences in boundary layer temperature in the Circumpolar Ocean, the sign of the difference (realization W_i minus realization M_i) is the same for all the "matched pairs". This enhances our confidence that the significant differences in this region are a robust result - unlike those in the area south of the Hudson Bay. Note also the close correspondence between areas with increases in Antarctic sea-ice coverage (Fig. 5c), decreases in boundary layer temperature (Fig. 5a; both in *W* relative to *M*), and high statistical significance of ensemble-mean differences in May 1987 boundary layer temperatures (Fig. 5b).

The Arabian Sea and western coast of India is another area where the *W* and *M* ensemble mean boundary layer temperatures are significantly different in May 1987 (see Figs. 5b, 7b). In this region, the monthly forcing data yield an ensemble-mean boundary layer temperature that is up to 0.4^{o}C colder than the ensemble mean for the higher-frequency SST and sea ice forcing (Fig. 7a). Over the Arabian Sea, the sign of this difference is consistently negative in all 18 "matched pairs" of *W* and *M* simulations – i.e., *M* is always colder than *W*. This result is unlikely to be fortuitous, and probably reflects a real difference in the climate response to the weekly versus monthly SST forcing. Results are more equivocal over the Indian subcontinent itself, where only 12 of the 18 matched pairs have cooler boundary layer temperatures in *M*.

There is some indication from Fig. 7c of a systematic difference in total precipitation, with the lower frequency SST forcing yielding decreases in precipitation rate of up to 3 mm/day in the Arabian Sea. This decrease, however, is significant at only a relatively small number of grid-points (see Fig. 7d). Overall, our results suggest that the temporal resolution of the SST forcing may have some impact on the representation of the Indian Summer Monsoon in the LLNL AGCM. Further study is warranted in order to determine whether this result is specific to the model used here or more general in nature.

3.3.2 Surface pressure

To investigate whether the atmospheric general circulation is noticeably modified by differences in the temporal resolution of the surface forcing, we examined surface pressure differences between the two ensembles. As in the case of temperature, differences between the *W* and *M* ensemble mean surface pressures vary both geographically (Fig. 8a) and seasonally (not shown). March 1987 has the largest number of grid cells with differences in ensemble mean that are significant at the 10% level or better (33.9% of the grid cells). During this month, differences in ensemble mean surface pressure are highly significant over large areas of the Arctic Ocean (Fig. 8b), where pressures in ensemble M are more than 5 mb higher than in ensemble W (Fig. 8a). Another region of significant surface pressure differences is the southern Indian Ocean.

3.3.3 Other variables

Table 1 also gives cumulative 5% and 10% *t*-test results for a number of other variables. Results are for the annual-means of the monthly mean percentages. Atmospheric boundary layer temperatures yield the largest fraction of significant 5% and 10% grid-point *t*-tests

(14.1% and 21.0%, respectively). Ensemble mean differences are least significant for clouds, radiative quantities and precipitation. The fact that some variables may be more sensitive to the temporal resolution of boundary conditions than others is not surprising and may have several explanations. First, different variables clearly have different levels of inherently unpredictable atmospheric variability (Wehner, 1998). Second, there are also likely to be real physical differences in the sensitivity of different quantities to the temporal resolution of the SST and sea ice forcing. The lack of a stronger signal in the surface turbulent heat flux, which is proportional to the vertical gradient of temperature between the ocean surface and the lower atmosphere, is probably due to the rapid adjustment of near-surface air to SST variations.

4 Overall Statistical and Physical Significance of Differences

Do the differences in the temporal resolution of the SST and sea ice boundary conditions yield differences in climate variables that are large enough to be of concern in AMIP-type experiments? In the previous section, we discussed some features of the ensemble-mean differences in boundary layer temperature, precipitation and surface pressure that arise from specification of boundary conditions based on weekly and monthly data. Our results indicate that some features of these differences achieve local significance (see, e.g., Figs 5b, 6b, 7b, 7d and 8b). The *t*-test results in Table 1 provide some information on which variables might be more sensitive to differences in the time resolution of the SST forcing. They do not, however, answer the question of the overall significance of the ensemble mean differences. To address this issue in a rigorous way would require accounting for the twin effects of multiplicity and spatial autocorrelation (Livezey and Chen, 1983; Wigley and Santer, 1990). Multiplicity can be accounted for by using the binomial distribution. Spatial autocorrelation is more difficult to account for, and requires determination of n_x^*, the effective number of independent points in the field, which is generally much less than n_x.

Our concern here is not with assessment of n_x^* and the formal statistical significance of overall differences between M and W ensemble means. Instead, we opt for a more pragmatic approach, and consider whether the separation of M and W ensemble means is greater than either inherent observational uncertainty or characteristic model errors (Santer *et al*., 1995; Gates *et al*., 1998, Taylor, 1998). Let us assume that the ensemble mean differences between M and W (for a given climate variable) are consistently smaller than the differences between two observational data sets or between the 'most skillful'[1] currently available model and observations. In this case, it is probably adequate, at the present stage of model development and for present observational uncertainties, to perform AMIP-type experiments with boundary conditions based on monthly mean data.

[1] We assume here that the determination of the 'most skillful' model is based on a variety of statistical measures (see, e.g., Gates *et al*., 1998) and likely depends on the climate variable under consideration.

In the following, we use an RMS statistic to compare $\overline{W} - \overline{M}$ differences with observational uncertainties and model errors. The statistic is simply an area-weighted spatial root-mean-square difference:

$$RMS = \sqrt{\sum_{x=1}^{n_x} [\overline{W}(x) - \overline{M}(x)]^2 / n_x}$$

We compute a similar RMS statistic for the differences between two 'observed' data sets – the reanalysis products produced by the National Center for Environmental Prediction (NCEP; Kalnay *et al*., 1996) and the European Centre for Medium-Range Weather Forecasts (ECMWF; Gibson *et al*., 1997). This statistic is also calculated for the differences between one reanalysis (NCEP) and the 'most skillful' AMIP model (Taylor, 1998) *for a particular field*. The same time periods are used in all RMS calculations ($\overline{W} - \overline{M}$, observational uncertainty, and model error), i.e., monthly mean data for March, May and August 1987. Results are given for three variables only – surface pressure, boundary layer temperature, and total precipitation rate. For the first two of these variables, RMS statistics are computed over ocean only. This simplifies the interpretation of RMS values by avoiding the effects of differences in procedures for calculating surface pressure and accounting for the fact that a "boundary layer temperature" comparable to that in the LLNL model is not directly available from the AMIP results.

Results are summarized in Table 2. Several general conclusions are evident from this. First, for the three variables and three months considered here, the differences between the W and M ensemble means are invariably smaller (by a factor of 5-10) than the RMS differences between the 'most skillful' AMIP I model simulations and observations. Second, with the exception of the surface pressure result for March 1987, $\overline{W} - \overline{M}$ differences are also consistently smaller than the RMS differences between the ECMWF and NCEP reanalysis products. (Note that this is not a true 'observational' uncertainty, since some component of the ECMWF minus NCEP differences is associated with the differences in the physics and resolution of the numerical models used in reanalysis; see Santer *et al*., 1998). Third, the RMS differences for observational uncertainty are consistently smaller than the differences attributable to model error.

The conclusion to be drawn from this is that the specification of more realistic SST and sea ice boundary conditions with enhanced temporal resolution (i.e., based on weekly mean data rather than on monthly means) is not likely to yield a significant reduction in current model-minus-observed differences. Such differences are probably dominated by large systematic model errors. Furthermore, differences in the mean climate states arising from use of monthly versus weekly boundary conditions are generally well within the current 'noise' of observational uncertainty.

5. Discussion and conclusions

We compared two different sets of daily SST and sea ice boundary conditions. One set was obtained from weekly means linearly interpolated to daily values, while the other was derived from monthly means interpolated to daily values. The differences between the two sets vary geographically and seasonally. For sea surface temperatures, the differences have essentially two origins: the monthly means interpolated to daily values do not resolve the variability at time scales less than one month, and this time series underestimates the actual seasonal maxima and minima (which is also true for weekly means, but to a lesser extent). Underestimates of the observed maxima in the monthly mean case are particularly apparent in the case of the sharp summertime maxima in the extratropical northern latitudes.

The purpose of this study was to determine whether atmospheric general circulation models should be forced with surface boundary conditions interpolated from weekly means instead of monthly means, the more commonly used method. As a case study, we tested the sensitivity of one AGCM to a change in the temporal structure of the sea surface temperatures and sea ice cover boundary conditions. The output from two ensembles of 18 simulations each was analyzed. In one ensemble, the model was forced by weekly mean values linearly interpolated to daily, in the other ensemble by monthly mean values interpolated to daily. Over the open ocean, the impact of different boundary conditions is generally low for the near-surface air temperature (temperature of the planetary boundary layer), because differences between the two sets of boundary conditions is also low (generally less than 0.5^{o}C). But when differences between the two sets of boundary conditions are maximum (during summer over the northern oceans), their impact on the simulations can be statistically significant. Over land and sea ice, the differences between the two ensembles can be large, but they are not statistically significant compared to the intra-ensemble variability.

A practical approach was taken to evaluate the overall statistical and physical significance of our results. The differences found between the weekly and monthly ensembles were compared with estimates of observational uncertainty and characteristic model errors. RMS differences between the ensembles were a factor of 5-10 smaller than the differences between the 'best' AGCM simulation and observations. With few exceptions, the ensemble differences were also found to be consistently smaller than the differences between two standard observational data sets. The conclusion drawn from these comparisons is that a higher frequency boundary condition forcing (i.e., weekly SST and sea ice instead of monthly) is unlikely to yield significant simulation improvements because of the dominance of model systematic errors. Additionally, differences between the mean climate of the two ensembles are well within current observational uncertainty.

Thus, at least with the model used in this study, the use of monthly means interpolated to daily values seems sufficiently realistic for a wide-range of diagnostic studies. This conclusion should also hold if a more sophisticated method of interpolation were used. Sheng and Zwiers (1998), for example, have suggested an alternative interpolation method that ensures the monthly mean computed from the interpolated daily values will be equal to the actual monthly mean. Taylor et al. (1997) have described how this technique can be generalized to treat sea ice and to ensure that temperatures always exceed the freezing point. They have also shown that this technique significantly reduces the underestimation of summer maximum temperatures, which are most apparent in the northern oceans. The Taylor et al. (1997) method has been adopted as the standard procedure for AMIP II.

The variability of sea surface temperature or sea ice extent at shorter than monthly time scales certainly has importance in the forcing of the atmosphere. However, it is not obvious that use of a higher frequency forcing (although present in nature) ensures an increasingly realistic AGCM simulation. Structures present at sub-monthly frequencies in the weekly mean observations can be the result of air-sea "weather" interactions, and while realistic, are almost certainly inconsistent with the simulated state of the atmosphere in lengthy integrations.

In conclusion, this study provides some justification for the continuing use of monthly-mean SSTs and sea ice as boundary forcing for AGCM experiments. Some specialized model analysis may warrant further testing however. For example, we have seen that the differences in the temporal sampling of surface boundary conditions can have some local impact (as in the monsoon region). Effects on shorter time scales (e.g., daily) that are important for the study of some processes have not been explored here. Moreover, it is important to emphasize again that the findings of this study are specific to one model. Further testing with an AGCM known to be more sensitive to boundary forcing should be considered. Finally, the analog experiment with ocean models, testing the sensitivity of the simulated circulation to the temporal structure of the wind stress forcing, also deserves attention.

Acknowledgments

This work was performed under the auspices of the U.S. department of Energy, Environmental Sciences Division, at the Lawrence Livermore National Laboratory (Livermore, CA, USA) under contract W-7405-ENG-48. The authors are grateful to J.-W. Kim and J. Boyle for their interest in this study and their valuable comments. ECS would like to thank W.L. Gates for hosting her stay at PCMDI during 1996-1997.

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Table 1

Weekly vs. Monthly ensemble differences: statistical significance by variable

Variable	*Percentage of grid cells with statistical significance:*	
	exceeding 95%	*exceeding 90%*
Atmospheric boundary layer temperature	14.1%	21.0%
Surface pressure	9.5%	16.6%
Latent heat flux	9.3%	15.8%
Sensible heat flux	8.4%	14.5%
Outgoing longwave radiation	7.9%	13.7%
Precipitation	6.5%	12.9%
Net radiative flux at top of atmosphere	6.9%	12.4%
Cloud cover (temporal percentage)	6.5%	12.1%

Table 2

Spatial RMS results

	March 1987			**May 1987**			**August 1987**		
Variable	W-M	Obs.*	Error#	W-M	Obs.	Error	W-M	Obs.	Error
Boundary layer temp. (^{o}C)	0.26	0.82	--	0.42	1.05	--	0.27	1.12	--
Surface pressure (hPa)	1.01	0.75	4.91	0.69	1.07	5.76	0.56	0.95	5.82
Precipitation (mm/day)	0.57	1.89	2.65	0.59	2.11	2.60	0.55	2.01	2.70

* Observational uncertainty, defined here as result for ECMWF minus NCEP reanalysis.

Model error, defined here as 'most skillful' AMIP I model (Taylor, 1998) minus NCEP reanalysis.

List of Figures

Fig. 1: (a) Temporal root mean square difference (^{o}C) for August 1987 between the daily values of SST obtained by linear interpolation of monthly mean observations and weekly mean observations (at a resolution of 1^{o}x1^{o}). (b) As in (a) but at a coarse AGCM resolution of $5^{o}\times 4^{o}$ (longitude x latitude).

Fig. 2: Time evolution over period 1983-87 of the monthly root mean square differences of sea surface temperatures interpolated to daily from monthly or weekly means in zonal average over the oceans.

Fig. 3: Time evolution of sea surface temperatures (^{o}K) linearly interpolated to daily from monthly means (solid curves) and weekly means (dashed curves), for selected regions. Each region corresponds to a grid cell at a typical AGCM resolution ($5^{o}\times 4^{o}$). (a) North Atlantic Ocean at Latitude 42N and Longitude 40W; (b) Circumpolar Ocean (42S, 50E); (c) East Equatorial Pacific (2N, 105W).

Fig. 4: (a) Temporal root mean square difference for August 1987 between the daily sea ice extent (in percent of area) obtained by linear interpolation of monthly mean observations and weekly mean observations. The horizontal resolution is $1^{o}\times 1^{o}$. (b): Same as (a) but for the Antarctic. Before RMS computation the ice cover is taken equal to 100% when the observational daily value is larger than 50% and 0% otherwise, as often done in AGCMs. The resolution is $5^{o}\times 4^{o}$.

Fig. 5: (a) Boundary layer temperatures (K): difference between the means of ensemble M and ensemble W for May 1987 (M minus W). (b) Statistical significance of the differences shown in (a) as determined from a Student T-test. (c) As in (a) but for sea ice (%).

Fig. 6: (a) and (b) As in Fig.5 a-b but for August 1987.

Fig. 7: (a) and (b): As in Fig.5 a-b but focusing on India and the Indian Ocean. (c) and (d): As in (a) and (b) but for precipitation (mm/day).

Fig. 8: (a) Surface pressure (in mb): difference of the means between ensemble M and ensemble W for March 1987. (b) Statistical significance of this difference.

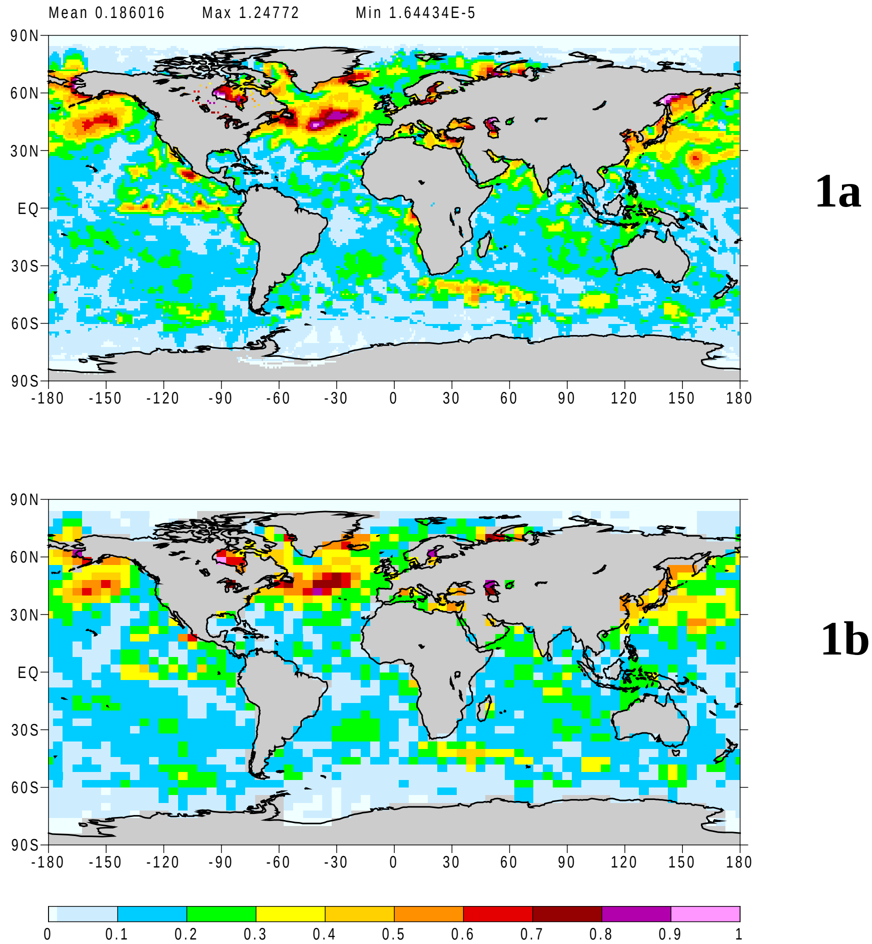


Fig.1: (a) Temporal root mean square difference (°K) for August 1987 between the daily values of SST obtained by linear interpolation of monthly mean observations and weekly mean observations (resolution:1°x1°). (b) Same as (a) but at a more common AGCM resolution (5°x4°).

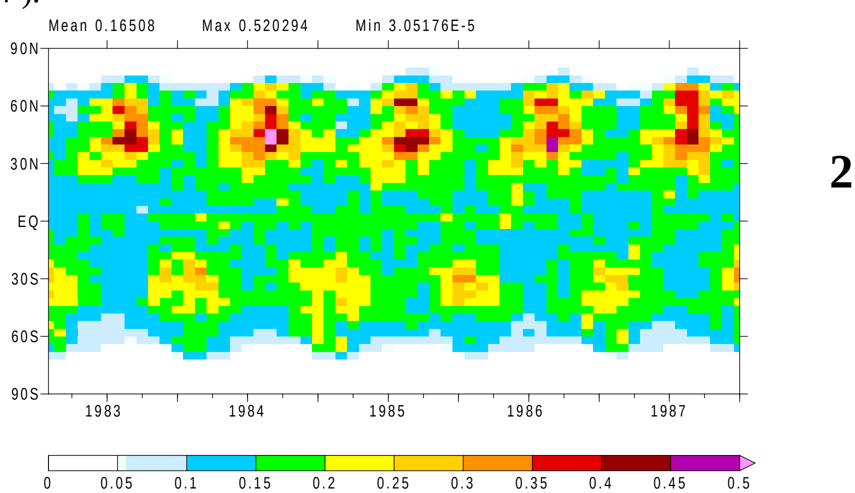
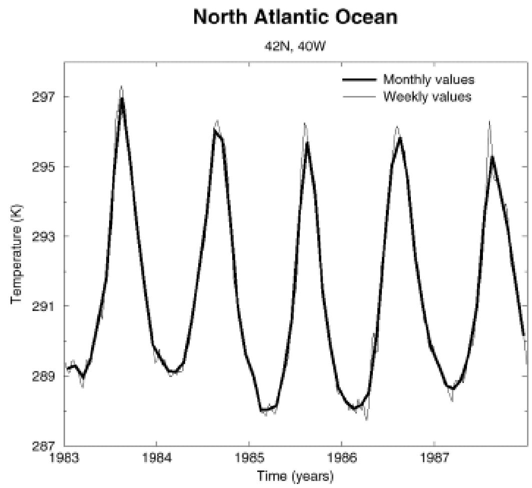


Fig. 2: Time evolution over 1983-87 of the monthly root mean square differences of daily SSTs (K) interpolated from monthly or weekly means, zonally averaged over the ocean.



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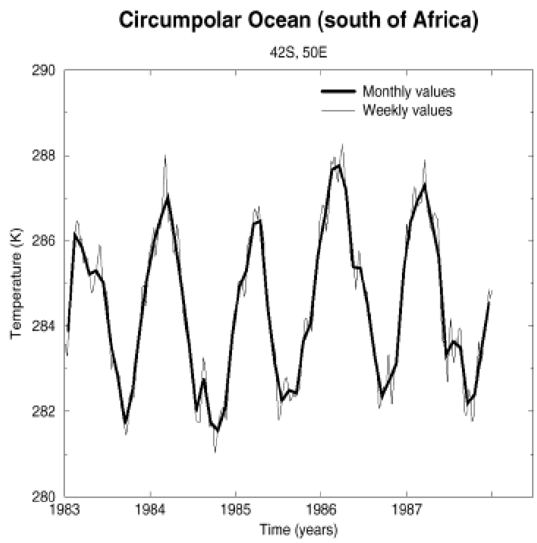

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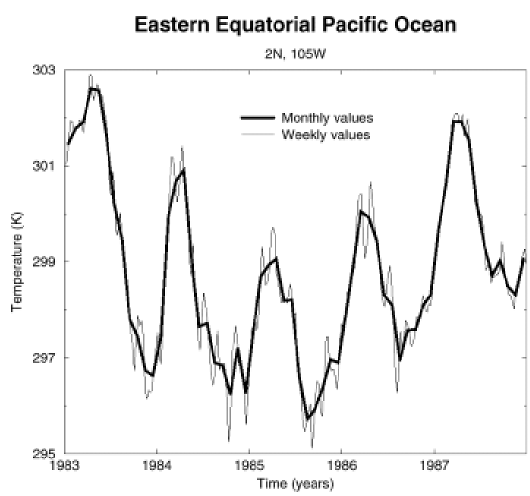

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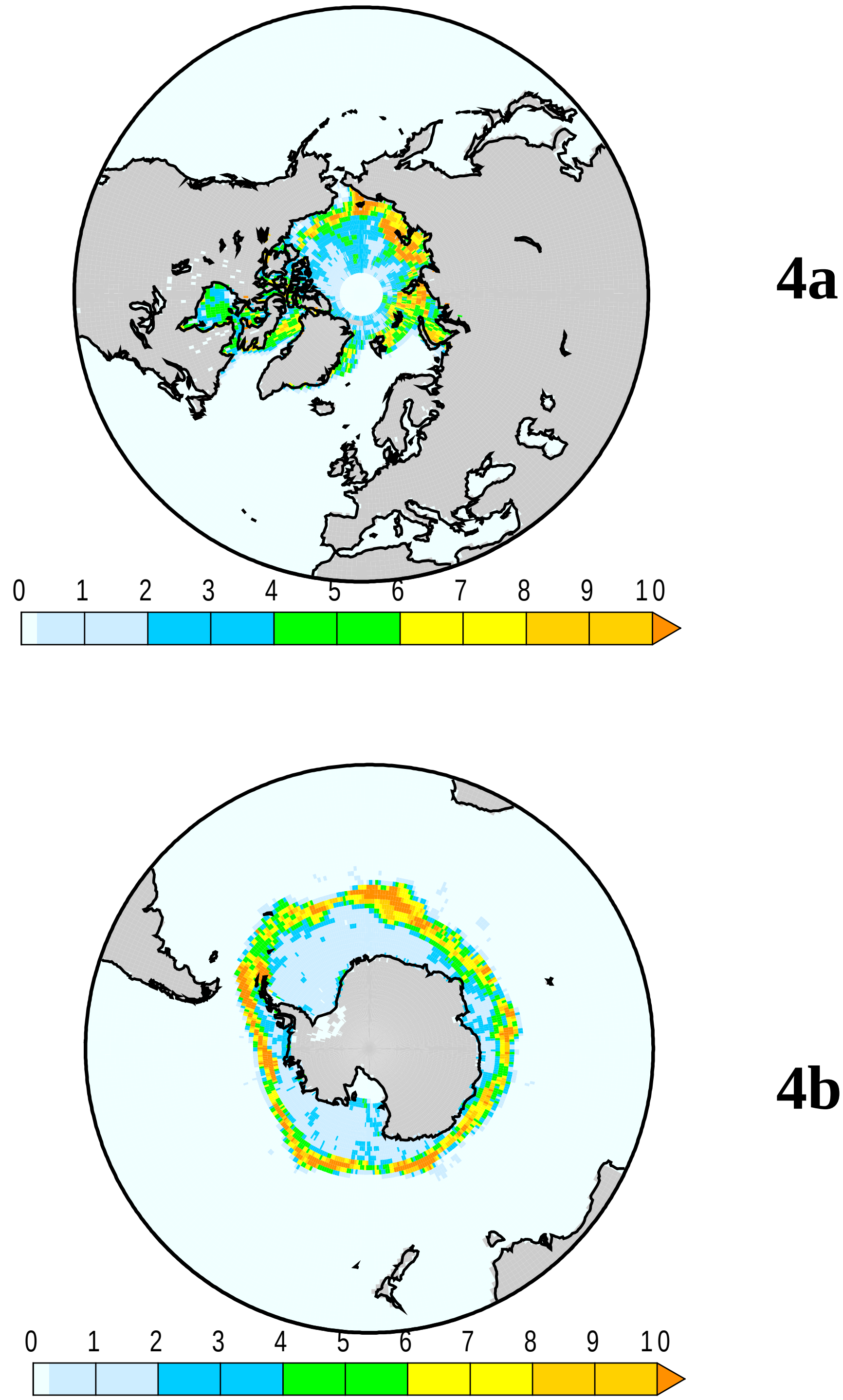
Fig. 3: Time evolution of SST (°K) linearly interpolated to daily from monthly means (solid lines) and weekly means (dashed lines), for selected regions. Each region corresponds to a grid cell at a common AGCM resolution (4° x5°). **a)** North Atlantic Ocean (42N, 40W); **b)** circumpolar ocean (42S, 50E): **c)** East equatorial Pacific (2N, 105W).



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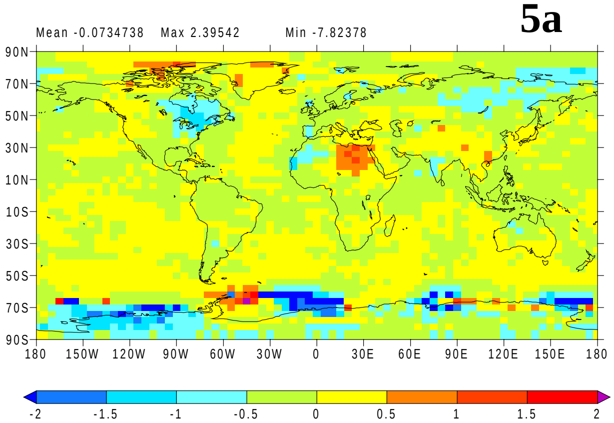
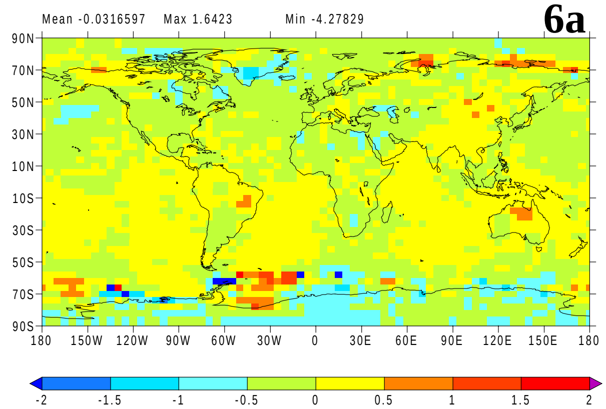
5a



6a



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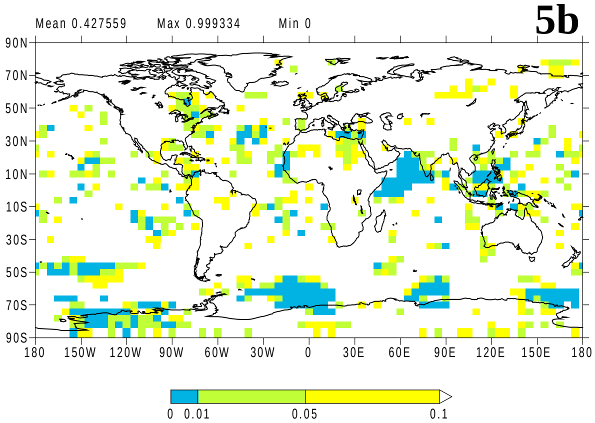

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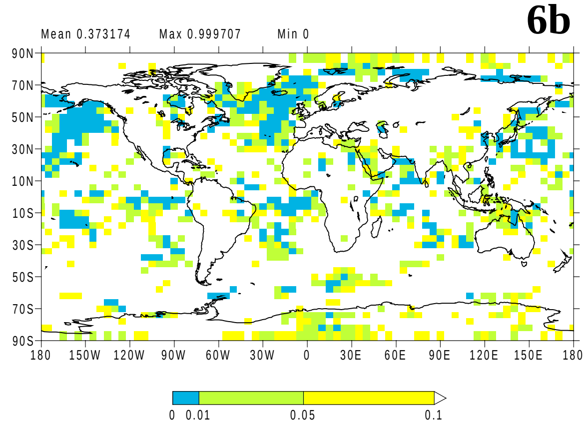

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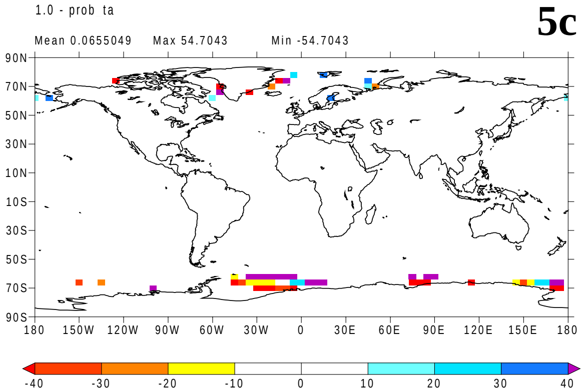

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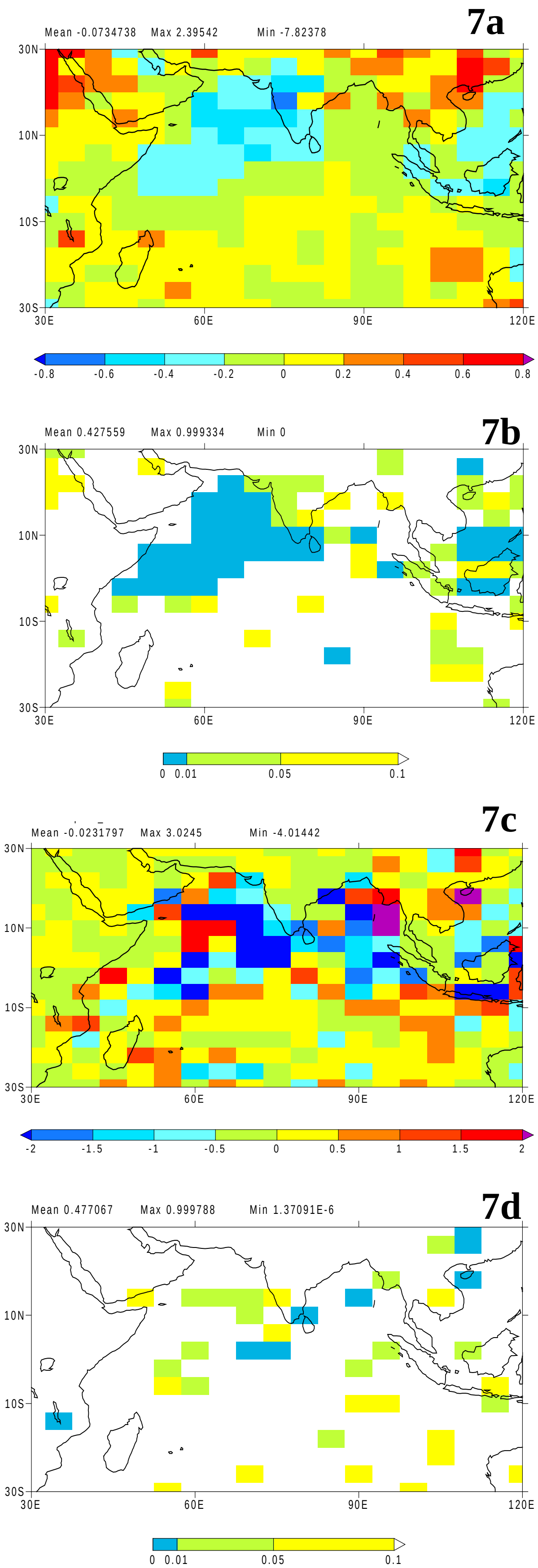

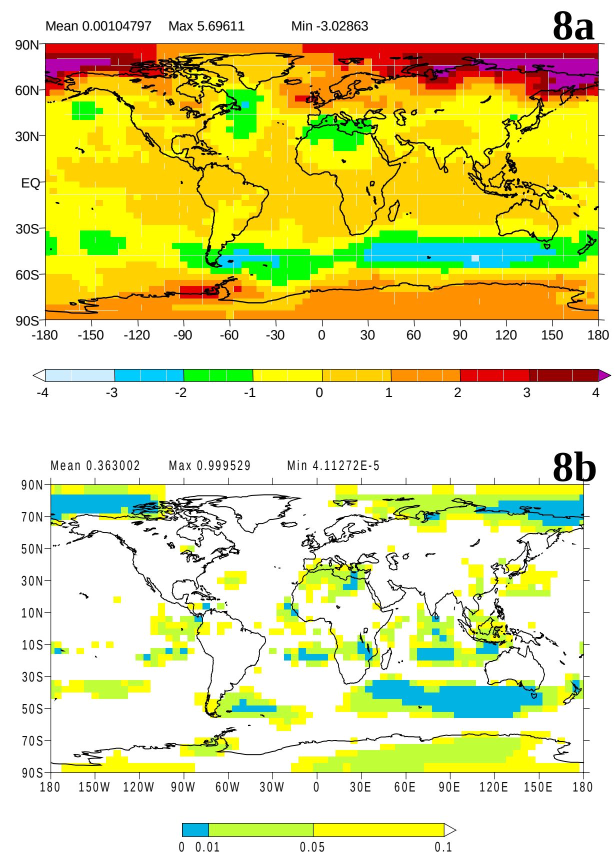

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