A Preliminary Intercomparison of the Seasonal Response of Two Atmospheric Climate Models

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ABSTRACT

In order to better identify and more fully understand the differences in sensitivity among climate models, two quite different models are systematically compared in terms of their seasonal response. The two-dimensional statistical dynamical model (SDM) developed at the Lawrence Livermore National Laboratory and the Oregon State University three-dimensional general circulation model (GCM) were integrated using as closely comparable boundary conditions and forcing as possible. Comparison of the seasonal anomaly (defined as the departure of the monthly zonal average from the zonal annual mean at each latitude) shows that the models agree quite well in terms of the seasonal phase and amplitude of net radiation simulated at the top of the atmosphere, the tropospheric average temperature and surface temperature and the precipitation. The models also resemble the observed seasonal anomalies of these variables to a reasonable degree, although there are significant errors in each formulation.

1. Introduction

Climate models differ widely in their geometry and resolution, and in their representation of atmospheric physical processes. Each of these factors affects a model's ability to simulate particular aspects of the climate, and each influences the model's ability to respond to perturbations that may be imposed in external forcing. Part of the variation that has been found among models in both control and perturbation experiments may therefore be due to the models' inherent differences, and part is due to the differences in forcing as perceived by the models. By comparing the performance of climate models under comparable conditions, it may be possible to identify their characteristic differences and to establish a calibration of their relative response. Such inter-model comparison is of particular value in the study of the climatic consequences of increased CO_2, in which a delineation of seasonal and geographical changes is desired but not readily available from all models.

Although some progress has been made in understanding the differences in the response of climate models of the same general type, such as one-dimensional radiative–convective models (Schneider, 1975) and general circulation models (National Research Council, 1979; World Meteorological Organization, 1979), much further and more systematic model intercomparison is necessary. In order to take full advantage of the hierarchy of models now available for climate sensitivity studies, it is particularly important to intercompare models of different types. Such a program of model intercomparison is an element of the World Climate Research Programme (World Meteorological Organization, 1981), and is a long-standing goal of the GARP/WCRP Working Group on Numerical Experimentation. The recent work of Coakley and Wielicki (1979) is an effort in this direction, although their analysis focused on an energy-balance model's ability to mimic only the radiative response of a more general model. Watts (1980) has also discussed the problem of intercomparing simple and complex models whose sensitivities may be similar but for quite different reasons.

The purpose of this paper is to examine the performance of two rather different climate models under as closely comparable conditions as possible and to try to interpret the results in terms of the models' inherent differences. Specifically, we shall compare the ability of the zonally-averaged Lawrence Livermore National Laboratory statistical-dynamical model (SDM) and the Oregon State University two-level general circulation model (GCM) to simulate the seasonal variation of the zonal averages of selected climatic variables that are common to both models when the insolation and sea surface temperature are prescribed to follow their observed climatological annual cycles. If the zonal model performs satisfactorily for such variables, then in some cases it may be unnecessary to use a GCM. On the other hand, use of the GCM will be required in studies where regional climate information or estimates of the climatic variance are the primary objectives. We plan to subsequently examine the relative performance of versions of these models which include an interactive upper ocean.

We recognize at the outset that each climate model will have a different level of accuracy in its simulation of the observed climate. The analysis of such model errors is an important part of a model's calibration or documentation, but it is not our present concern. Rather, we here attempt to display the model's inherent differences by considering their *relative* sensitivity or response to a prescribed climatic perturbation, such as seasonal solar forcing. For this purpose we have selected the seasonal cycle as the response against which we shall examine the relative sensitivities of the two models under standardized conditions. In so doing we hope to develop a methodology of intercomparison that may be useful when other factors such as the CO_2 content are changed.

2. Summary of the models

For this initial intercomparison it was decided to use two relatively well-documented models in current use: the atmospheric general circulation model of Oregon State University (OSU) and the zonal statistical–dynamical model of the Lawrence Livermore National Laboratory were therefore convenient choices.

The OSU GCM is a two-level global model with 4° latitude and 5° longitude resolution. At the model's interior σ-levels (located at the midpoints of two layers of equal mass between the surface and the model top at 200 mb), the velocity, temperature, geopotential and water vapor mixing ratio are carried as prognostic variables, with the temperature, pressure and surface moisture also predicted at the ground. The model predicts cloudiness as a result of either convective or large-scale condensation, and may simulate a snow cover as part of the surface hydrology. In its normal configuration the model has both diurnal and seasonal variations of solar radiation, and uses prescribed (climatological) distributions of sea surface temperature and sea ice.

The Livermore zonally-averaged model (or SDM) has 10° latitude resolution and nine isobaric levels in the vertical, five of which are at or above 200 mb. The model's dependent variables are the velocity, temperature, geopotential and mixing ratio, together with the surface pressure, temperature and humidity. Like the GCM, the SDM predicts cloudiness, precipitation and snow depth, and utilizes prescribed solar radiation and sea surface temperature in its standard version. Unlike the GCM, however, the SDM does not resolve regional or synoptic-scale changes and parameterizes the horizontal and vertical eddy transports.

A schematic summary of the vertical structure of the two models is given in Fig. 1. The Livermore model (LSDM) was modified by MacCracken (1968) from a two-dimensional version of Leith's (1965) GCM, and thus incorporates many features usually incorporated in a GCM. The present version of the LSDM is the

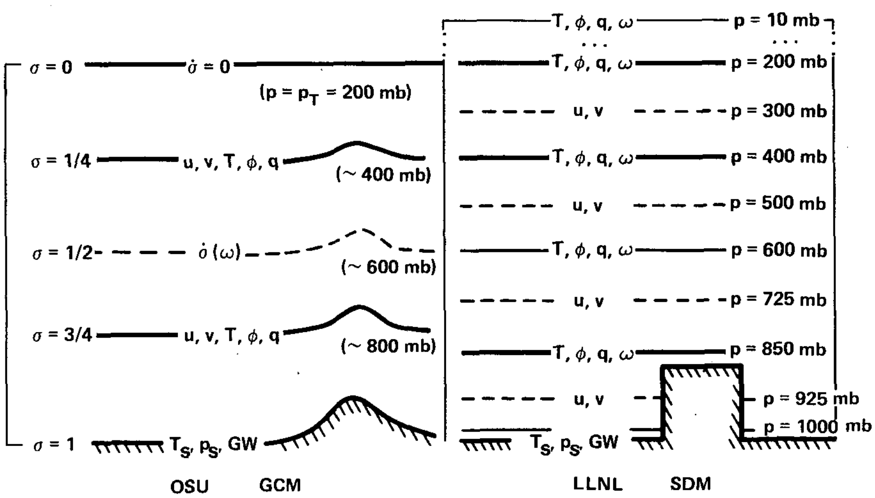

FIG. 1. The comparative schematic vertical structure of the Oregon State University two-level global general circulation model (GCM) (left) and the Lawrence Livermore National Laboratory zonally-averaged statistical-dynamical model (SDM) (right). Here the σ-levels of the GCM and the p-levels of the SDM are shown (except the levels at 20, 50, and 100 mb for the SDM), where the temperature (T), geopotential (ϕ), water vapor mixing ratio (q), and the horizontal (u, v) and vertical velocities (σ, ω) are predicted. Both models also predict the temperature (T_s), pressure (p_s) and ground wetness (GW) at the surface, although in slightly different ways (see Ghan *et al.*, 1982; and MacCracken *et al.*, 1981, for model details).

result of a sequence of developments (MacCracken, 1972; MacCracken and Luther, 1974; Luther and MacCracken, 1974; Potter *et al.,* 1979), and has recently been described by MacCracken *et al.* (1981). The OSU GCM has its origin in the Mintz-Arakawa 2-level model developed at UCLA in the late 1960s, and has been used in a number of short-term climate experiments (Gates, 1975) and seasonal control simulations (Gates and Schlesinger, 1977, and Schlesinger and Gates, 1980). A comprehensive documentation of the present control version of the OSU GCM has recently been prepared by Ghan *et al.* (1982).

3. Intercomparison strategy and boundary conditions

Key elements of our intercomparison strategy are the use of comparable boundary conditions for parallel integrations of the two models and the analysis of the models performance in terms of variables contained in both models. Since our primary aim is an evaluation of the models' relative sensitivity, our analysis procedure also involves the removal of the annual average of the variables simulated by each model. In this way the models' monthly response to the annual cycle in solar flux is seen in terms of the monthly departures from the zonal annual mean at each latitude. Such data clearly display the seasonal amplitude and phase of the selected climatic variables, even though the two models' actual performance relative to obervation is different. The resolution differences of the models also restrict the information that can be directly intercompared. In this preliminary study we have for convenience focused on the vertical integrals of selected variables and on fluxes at the top or bottom of the atmosphere that are common to both models without vertical interpolation.

In the SDM integrations the zonal average of the surface boundary conditions used in the GCM were employed in order to represent the surface in a consistent manner in the two integrations. This involved the zonal averaging of the boundary data of the GCM at 4° latitude intervals, and its interpolation onto the 10° latitudinal grid of the SDM for the climatological sea-surface temperature, surface albedo and elevation, and for the fractional area of land, ocean and sea ice. The seven surface types maintained by the GCM for the purpose of albedo identification were approximated by the five used in the SDM, with the snow cover (which is not fixed in either model) permitted to change the surface albedo and to accumulate or melt, depending on the simulated surface temperature. Both models compute the ocean albedo as a function of the solar zenith angle, but the albedo of land surfaces is not varied with the soil moisture. The initial conditions used in the integrations were taken from earlier control simulations of the two models, and their lack of coincidence is not believed to have an important influence on the climate of the interannual solutions considered here.

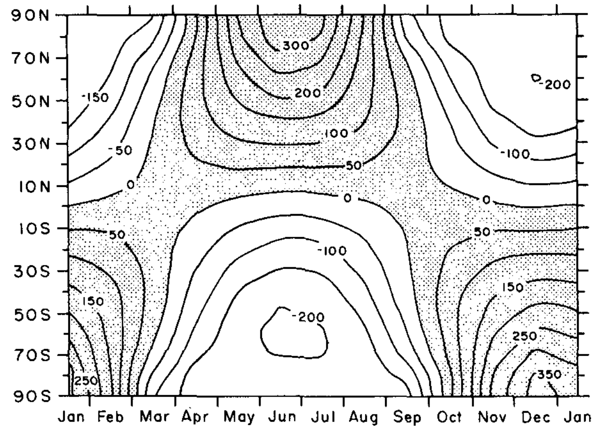

FIG. 2. The seasonal anomaly of the incident solar radiation at the top of the atmosphere, (W m^{-2}), i.e., the departure of the monthly zonal average from the zonal annual mean at each latitude. The positive anomalies in this and subsequent figures are shaded.

The zonally-averaged seasonal anomaly of the solar flux incident at the top of each model atmosphere is shown in Fig. 2, with the seasonal anomaly of the zonal mean of the imposed sea-surface temperature shown in Fig. 3. The seasonal anomalies of the corresponding fields are in the format in which most of our comparisons will be made, i.e., they show the departures of the simulated zonal average from the zonal annual mean at each latitude. While this display adequately represents the magnitude and phase of the seasonal cycle at each latitude separately, care must be taken in comparing the variation of this anomaly at different latitudes. Fig. 3, for example, shows that the largest ocean warming (relative to the zonal annual mean) occurs near 40°N, but this is not the latitude of the warmest water (relative to the global annual mean). Figs. 2 and 3 therefore show only the latitudinal asymmetry of the seasonal variation of the principal boundary conditions imposed on the models.

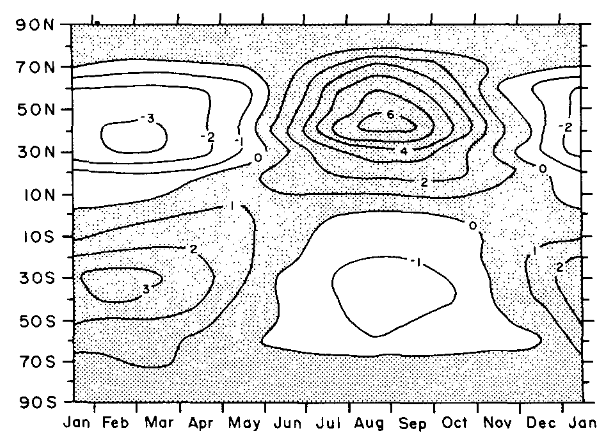

FIG. 3. The seasonal anomaly of the prescribed climatological sea surface temperature (K), taken from the monthly data of Alexander and Mobley (1976).

4. Response to seasonal forcing

Starting from initial conditions taken from an earlier integration which was in near statistical equilibrium, both models were run for three simulated years over which the models' seasonal response was averaged.[1] During these integrations the models' response to the seasonal forcing imposed via the boundary conditions has been systematically examined for a wide variety of climatic variables and processes. The present intercomparison, however, is limited to fields for which observational data are readily available and which are compatible with the intercomparison strategy described earlier; these include the net radiative flux at the top of the model atmospheres, the surface and mean tropospheric air temperature, and the simulated total cloudiness, the planetary albedo and the precipitation. The seasonal and interannual variability simulated by the models are not considered here, and have been discussed elsewhere for the GCM (Schlesinger and Gates, 1981); preliminary indications are, however, that the SDM's interannual variability is substantially smaller than that of the GCM, as might be expected given the absence of the high-frequency synoptic systems in a zonally-averaged model.

a. Net radiation

The net radiation at the top of the (model) atmosphere is given by the difference between the net incoming solar flux and the outgoing infrared flux; the former is affected by scattering in the atmosphere and by reflection from both clouds and the surface, while the latter is a function of the thermal radiation from the atmosphere, clouds and surface. Fig. 4 shows the average relative annual cycle (i.e., anomalies with respect to the annual mean at each latitude) of the net radiation observed at the top of the atmosphere (Stephens *et al.*, 1981), along with that simulated by the GCM (at 200 mb) and the SDM (at 0 mb) during their respective 3-year integrations. Since the incoming solar radiation (Fig. 2), the sea surface temperature (Fig. 3), and the location and albedo of sea ice have been prescribed from observation in both models, we would expect both models to reproduce the major features of the observed seasonal amplitude and phase. We note, however, that both models exaggerate the maximum of net downward radiation found in the summer hemisphere. We can partially account for this difference by noting (as shown later) that both models underpredict the cloudiness in midlatitudes in summer, which would result in more solar radiation being absorbed by the earth–atmosphere system with a consequent warming were it not for the fact that the ocean temperatures are not allowed to change. In the GCM this error occurs in spite of the fact that the prescribed downward solar flux at 200 mb is slightly less than that imposed at the top of the actual atmosphere in order to account for stratospheric ozone absorption. In general, the seasonal amplitude and phase of the net radiation simulated by the GCM are closer to ob-

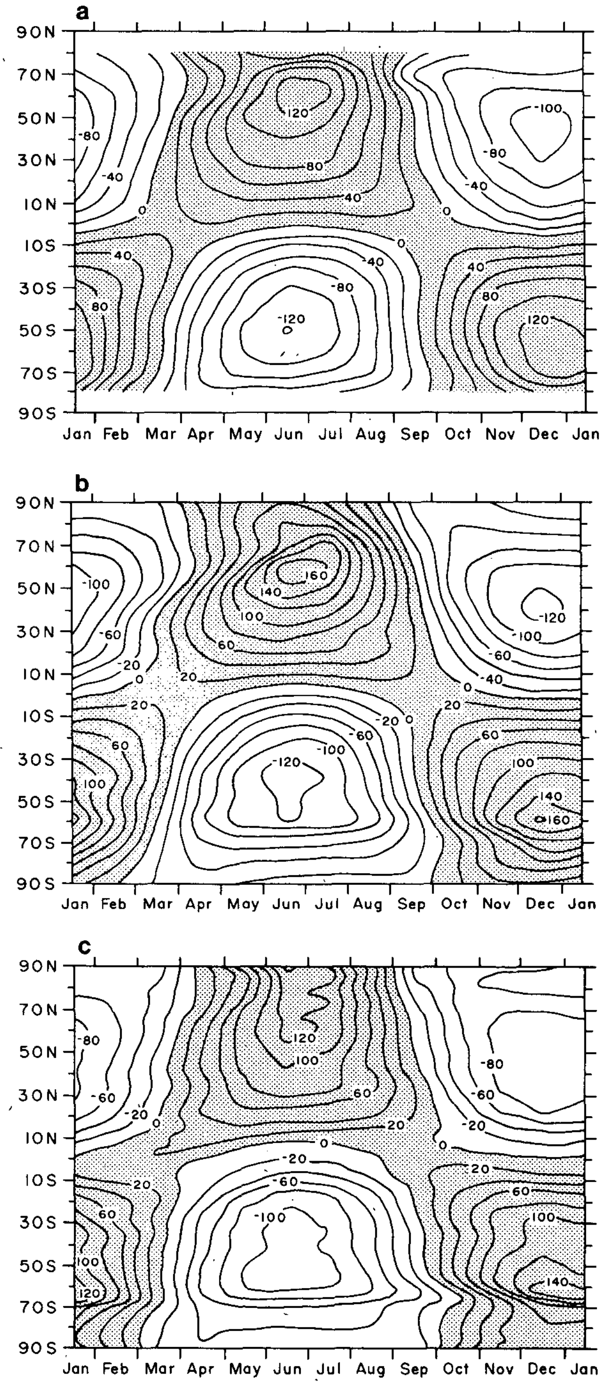

FIG. 4. Seasonal anomaly of zonally averaged net radiation at the top of the atmosphere (W m^{-2}) from (a) Stephens *et al.* (1981), (b) SDM, (c) GCM.

[1] The SDM's seasonal response showed no distinguishable differences over the three-year simulation.

servations than those produced by the SDM. On the other hand, the GCM produces a sharp gradient of the simulated net radiation near 70°S which is less realistic than that produced by the SDM. This feature is evidently a result of the albedo assigned to the prescribed sea ice in the models.

b. Cloudiness and planetary albedo

The variation in zonal mean observed cloud cover is shown in Fig. 5a, from the data of Berlyand and Strokina (1980). A prominent feature here is the summer maximum cloudiness in high latitudes, particularly in the Northern Hemisphere, which can be attributed to summer stratus (Ramanathan and Dickinson, 1981); as shown in Figs. 5b and 5c, neither model reproduces this feature well. In fact, the variation of cloud cover in the SDM in high latitudes is six months out of phase with observations, while the variation in the GCM is not much better.

Another major seasonal variation in cloudiness occurs in the tropics in association with the latitudinal excursions of the ITCZ. While both models reproduce the seasonal cycle in tropical cloudiness quite well, in the Northern Hemisphere the simulated subtropical summer cloudiness minimum is extended into middle or even high latitudes. The effect of this summer clearing on the net radiation at the top of the atmosphere has already been noted in the case of the SDM, and may be due to a too intense downward branch of the Hadley circulation resulting from the model's use of an annual rather than monthly average eddy momentum transport. The GCM cloud cover, on the other hand, occurs where there is precipitation, and indicates a less severe summer minimum than that indicated by the SDM.

The seasonal variation of the observed planetary albedo is presented in Fig. 6a. The albedo variation in low latitudes generally follows the variation in cloud amount resulting from the latitudinal migration of the ITCZ. This seasonal variation is simulated by both the SDM and GCM as shown in Figs. 6b and 6c, but with a greater amplitude. The seasonal albedo response in midlatitudes also appears to be dominated by changes of cloud amount in both models.

Because of the models' poor simulation of polar summer cloudiness, it is not possible to evaluate the relative roles of cloudiness and ice and snow cover in the changes of seasonal planetary albedo in high latitudes.

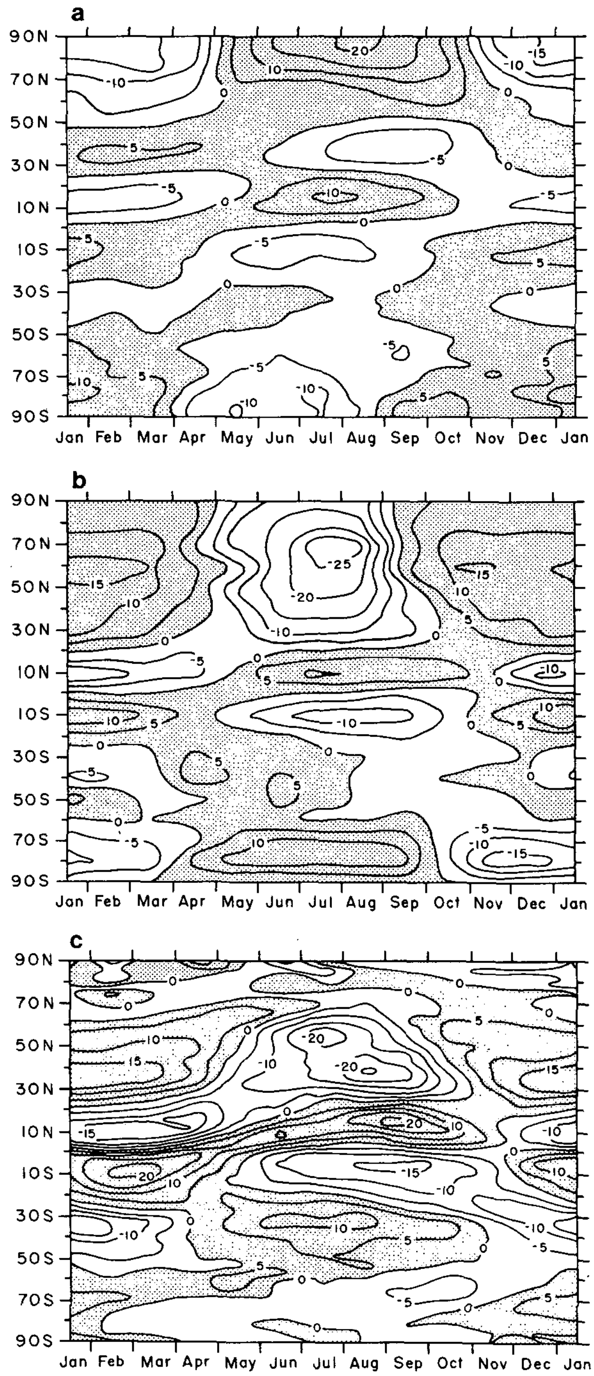

FIG. 5. Zonal mean seasonal anomaly of the zonally averaged total cloud cover (percent) from (a) Berlyand and Strokina 1980, (b) SDM, (c) GCM.

c. Temperature

The relative annual variation of surface air temperature is shown in Fig. 7, in which both models are seen to simulate the boundary layer temperature in close accord with that observed (Oort, 1983). This response is probably dominated in the Southern Hemisphere by the sea-surface temperatures prescribed from observations, and in the Northern Hemisphere by the seasonal cycle of solar radiation. We may note that the GCM reproduces the observed seasonal amplitude of the surface air temperature in the Southern Hemisphere summer only slightly less successfully than in the Northern Hemisphere winter. In contrast, the SDM

An interesting aspect of the observed precipitation dis-

(c) GCM.

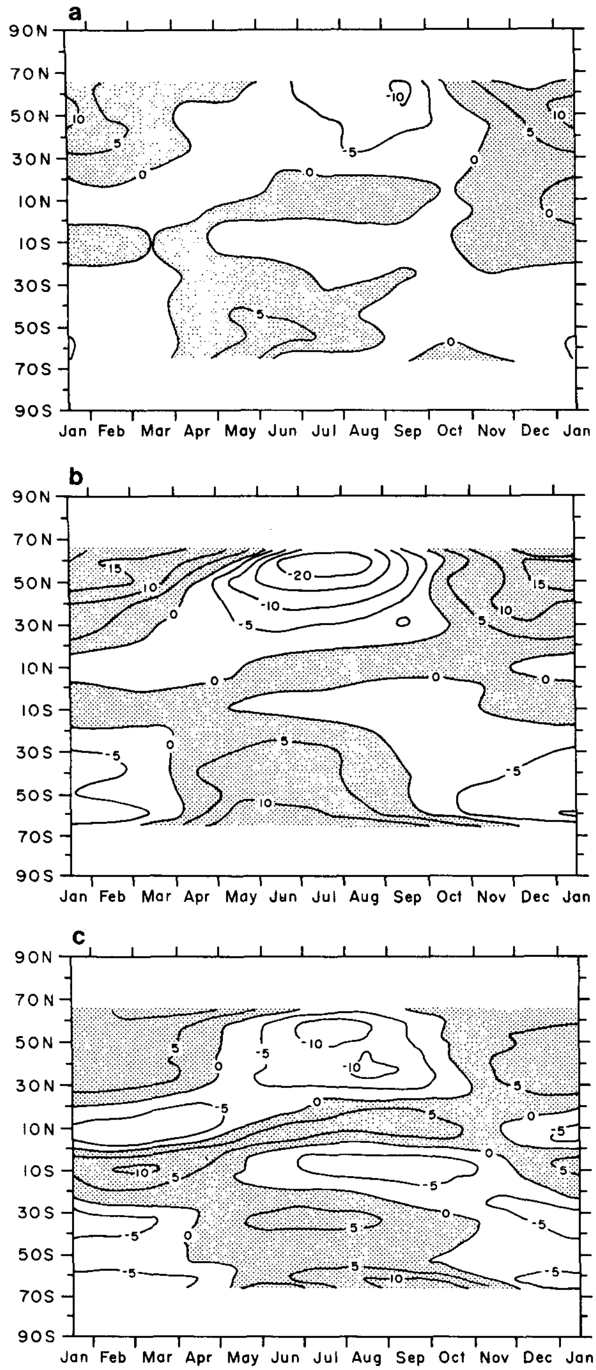

FIG. 6. Zonal mean seasonal anomaly of the planetary albedo (percent) from (a) Ellis and Vonder Haar (1976), (b) SDM, (c) GCM. The zonal seasonal anomalies poleward of 66.5° are undefined.

shows good agreement with observation in the Northern Hemisphere winter, but is less successful in predicting the maximum deviation from the mean in high southern latitudes.

The mass-weighted vertical averages of the models' simulated tropospheric temperatures are shown in Fig. 8. The seasonal amplitude and phase are seen to be in quite close agreement with each other and with observation, although the SDM has a slightly higher amplitude in northern latitudes than does the GCM, an effect due to the summer cloud minimum simulated by the SDM.

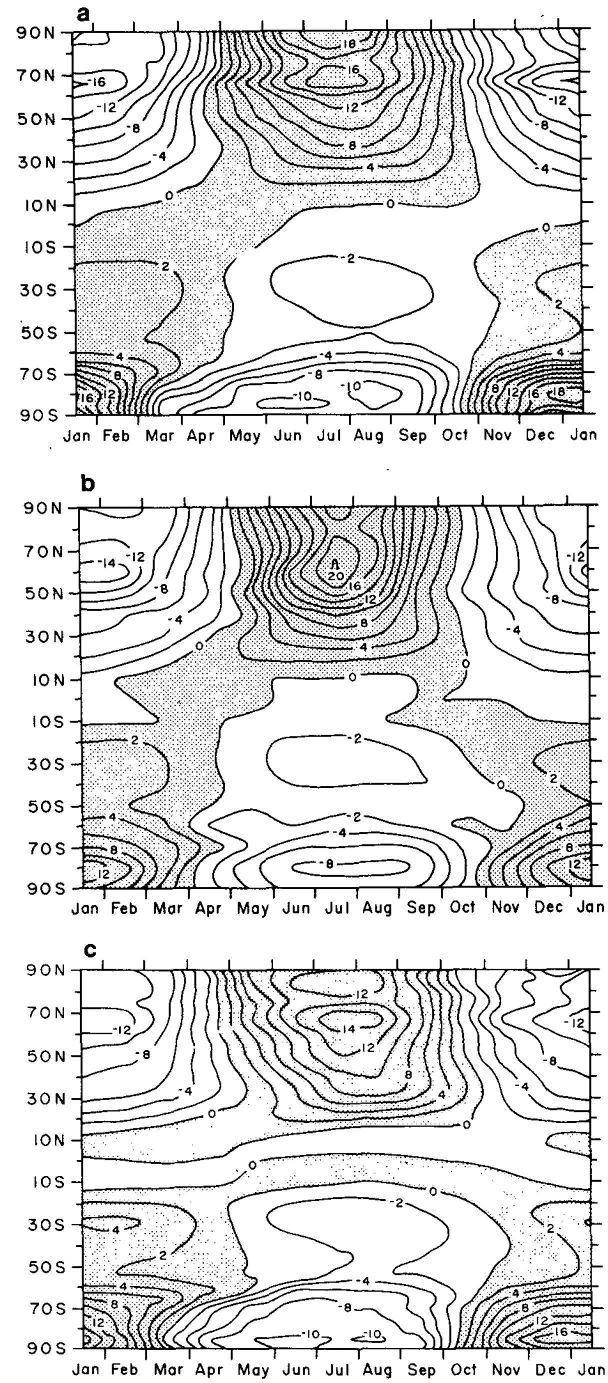

FIG. 7. Zonal mean seasonal anomaly of surface air temperature (K) from (a) Crutcher and Meserve (1970) and Taljaard *et al.* (1969), (b) SDM, (c) GCM.

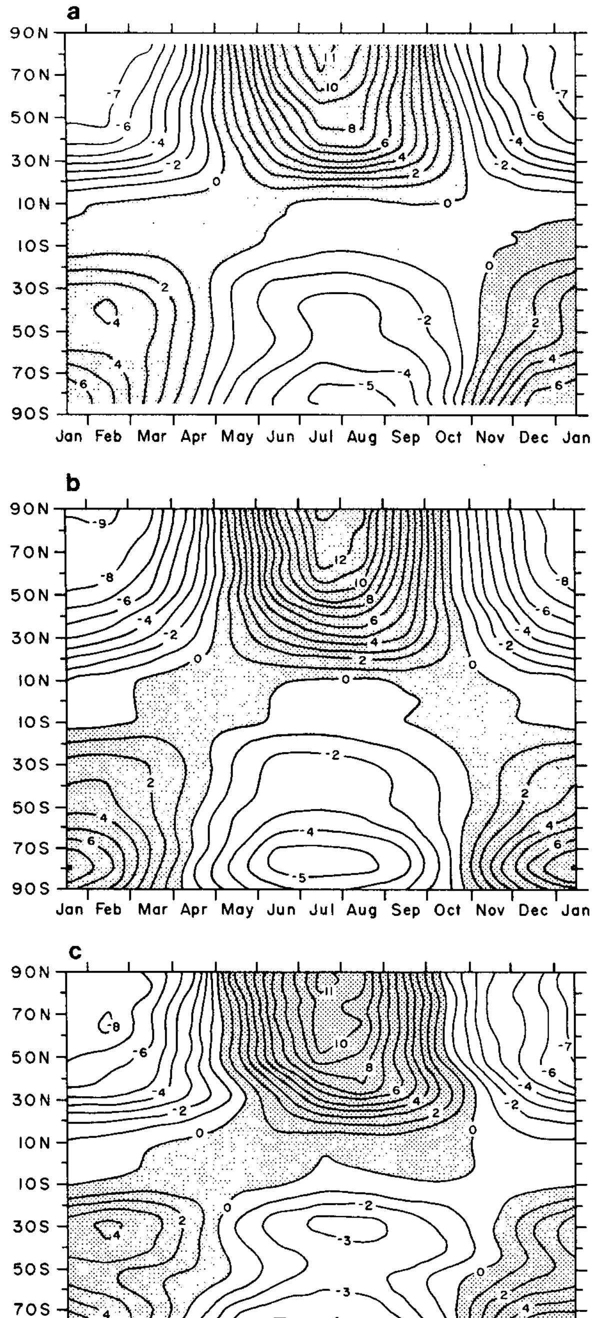

FIG. 8. Zonal mean seasonal anomaly of mass-weighted tropospheric temperature (K) from (a) Oort (1983), (b) SDM, (c) GCM.

d. Precipitation

The observed relative annual cycle of precipitation given in Fig. 9a clearly shows the effects of the movement of the ITCZ on the zonal mean precipitation. An interesting aspect of the observed precipitation distribution is the large deviation from the annual mean in the middle to high southern latitudes. The deviations here are nearly as great as those in the tropics, yet the total rainfall in those latitudes is considerably less. This feature may be due to the uncertainties of Jaeger's (1976) data which show summer and winter maxima

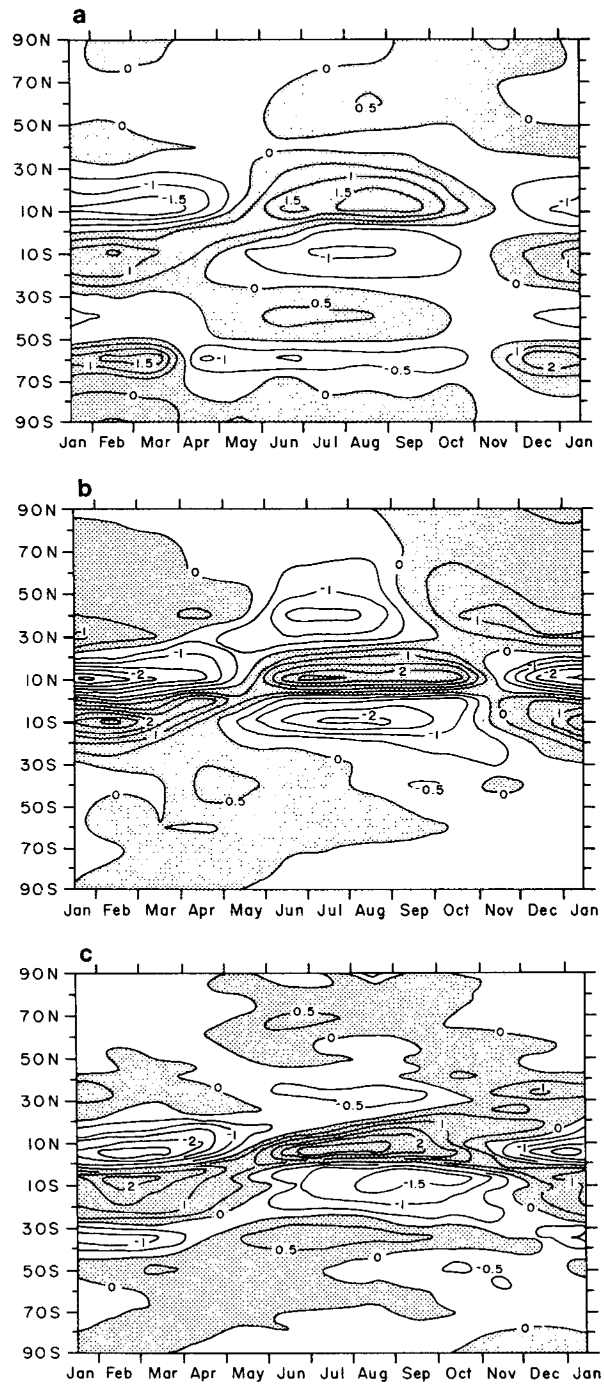

FIG. 9. Zonal mean seasonal anomaly of precipitation rate (contoured in intervals of 0.5 mm/day) from (a) Jaeger (1976), (b) SDM, (c) GCM.

of 4–5 mm day^{-1} in the Southern Hemisphere that are not found in Möller's (1951) data. With this exception, the relative annual variation of the precipitation simulated by the SDM and GCM shown in Fig. 9b and 9c satisfactorily reproduces the amplitudes associated with the seasonal excursion of the ITCZ (although the GCM maximum in the Northern Hemisphere summer occurs about a month too early). The SDM simulates the precipitation in the tropics reasonably well, but produces an extensive dry area in the northern middle and high latitudes associated with excessive tropospheric subsidence poleward of the ITCZ. The GCM simulates a similar drought associated with the movement of the subtropical high, while poleward there is an increase in summer precipitation similar to that observed (which the SDM fails to show). The agreement of both models' simulated precipitation in the tropics with that observed is probably due to the strong influence of sea-surface temperature on low-latitude precipitation.

e. *Summary of seasonal response*

Calculation of the amplitude and phase of the first harmonic of the annual cycle (as distinct from the seasonal anomalies presented in Figs. 4–9), shows that the SDM and GCM provide reasonably accurate portrayals of the seasonal variation of mean tropospheric temperature, although this agreement is greatly aided by the models' use of observed monthly sea-surface temperatures. For precipitation, the amplitude of the SDM's first harmonic exceeds that of the GCM (and observation) in the tropics and northern mid-latitudes, while the SDM's phase lags the observed phase by several months; the GCM's phase is closer to observations since it provides a better simulation of the Asian monsoon. The observed maximum amplitude of precipitation occurs in July in the Northern Hemisphere tropics and is reproduced well by both models. Although the total cloud cover is not simulated well by either model, the amplitude of the first harmonic of the SDM exceeds that of the GCM (and observations) in northern midlatitudes and is out of phase by nearly six months. The GCM's amplitude, on the other hand, is excessive in the tropics. In general, both models simulate the amplitude of the first annual harmonic better than they simulate the phase of the variables examined.

5. Concluding remarks

In this preliminary comparison of the seasonal performance of the Livermore SDM and the OSU GCM, we have used the same observed seasonal sea surface temperature and sea–ice distributions, and run both models over the same (three-year) period. By examining the relative zonal annual cycle (i.e., the monthly zonal average minus the annual zonal average) for variables common to both models, we have emphasized the models' relative seasonal sensitivity rather than their absolute accuracy.

Our overall conclusion is that both the zonal SDM and the global GCM produce similar seasonal phases and amplitudes of the (zonally-averaged) cloudiness, temperature and precipitation in response to the observed variations of incoming solar radiation and sea surface temperature. This similarity of response or sensitivity occurs in spite of the many differences in the models' structure and formulation, and may be an important consideration in the design of future model studies of the climatic response to increased atmospheric CO_2.

Among the questions that require further attention are the determination of the statistical significance of the differences simulated by the models, analysis of the atmospheric energy cycle of both models, and the analysis of integrations with freely calculated sea surface temperatures. From such analyses, we hope to develop a quantitative basis for the selection and interpretation of a particular model's response in other climate change experiments, including the response to increased CO_2 concentrations.

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