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Numerical Experiments on Short-Term Meteorological Effects of Solar Variability

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A set of numerical experiments has been carried out to test the short-range sensitivity of a large atmospheric general circulation model to changes in solar constant and ozone amount. On the basis of the results of 12-day sets of integrations with very large variations in these parameters, it is concluded that realistic variations would produce insignificant meteorological effects. Thus any causal relationships between solar variability and weather, for time scales of two weeks or less, will have to rely upon changes in parameters other than solar constant or ozone amounts, or upon mechanisms not yet incorporated in the model.

The study of possible physical mechanisms by which solar variability might influence weather (on time scales of a few days or weeks) is difficult both because the effects are apparently weak and because the causes are probably complicated. Recent examples of the types of effects for which explanations are sought include statistical relationships between atmospheric vorticity indices and either geomagnetic storms (Roberts and Olson, 1973) or the solar magnetic sector structure (Wilcox et al., 1973). Because the energy variations associated with solar variability are small compared to the total output of solar energy, and because the more direct effects are likely to occur in the high atmosphere, it has long been recognized that any causal chain of physical mechanisms is likely to involve trigger effects or coupling processes (London, 1956; Monin, 1972).

In the present work we have investigated two possible influences on the weather by numerical experiments with a large general circulation model of the atmosphere. In terms of physical completeness, overall realism, and sheer computational complexity, such models represent current state-of-the-art capability for large-scale weather forecasting and climate simulation. However, they do not include many proposed possible physical mechanisms connecting solar variability and weather. It seems worthwhile, nevertheless, to explore the sensitivity of such a model to those influences which it does attempt to take into account. We have therefore tested the response of our model to changes in atmospheric ozone content and to changes in the solar constant.

THE MODEL AND ITS LIMITATIONS

The model used in this study is a nine-level primitive equation, general circulation model with a horizontal finite-difference grid spacing of 4° in latitude and 5° in longitude (see Somerville et al., 1974, for a detailed description). The domain is global, and a realistic distribution of continents, oceans, mountains, and snow and ice cover is included. The model contains detailed computations of the heat balance at the surface and of the hydrologic cycle in the atmosphere. Its calculations of energy transfer by solar and terrestrial radiation make use of model-generated fields of cloud and water vapor. Parameters used in the parameterization of the solar radiation (Lacis and Hansen, 1974) include ozone absorption, the diurnal variation of solar zenith angle, and the diurnal and seasonal variation of solar flux. The amount and vertical distribution of ozone in the model are based on results summarized by Manabe and Möller (1961). These quantities vary latitudinally and seasonally.

This model has produced a realistic simulation of tropospheric, January climate (Somerville et al., 1974) and has demonstrated a 2-day forecasting skill equal to that of current, operational, numerical weather-prediction models (Druyan, 1974). The model is thus appropriate for the time scales (up to about 2 weeks) involved in the present work.

The model is limited, for the purpose of this study, primarily by a vertical resolution of about 110 mb, by a top at 10 mb, and by the omission of any coupling with the very high atmosphere. Additionally, a climatological distribution of sea surface temperature is prescribed. The model is therefore unsuitable for investigating processes involving changes in sea surface temperature, but such changes typically occur on time scales which are long compared to those which characterize the previously cited statistical relationships between solar or geomagnetic variables and meteorological ones.

EXPERIMENTAL PROCEDURE

In view of the capabilities and limitations of the model, we have employed the following procedure to determine the sensitivity of the evolution of the atmosphere as predicted by the model to changes in solar constant and ozone amount: First, we perform a control run by integrating the variables given by the model from a particular initial condition, specified by meteorological observations at 0000 GMT, December 20, 1972, as supplied by the National Meteorological Center. We perform the integrations for 12 days. Next, we carry out a second set of integrations to measure the natural variability of the model atmosphere. This set of integrations differs from that of the control run only in that the initial state is created by modifying that of the control run by random perturbations with RMS amplitubes of 1 K in temperature and 3 m/sec in wind at all grid points, and 3 mb in pressure at all surface grid points. Because such pairs of sets of integrations can be used to estimate the effect of observational uncertainty on atmospheric predictability, we denote this second set of integrations as the predictability run.

Since we anticipate that realistic changes in the solar constant and the amount of ozone would cause effects too weak to be detected except by a Monte Carlo procedure involving many sets of integrations of the model's variables (Leith, 1973), we artificially increase the signal-to-noise ratio by performing several sets of integrations with unrealistically large changes in solar constant and ozone amount. Such sensitivity studies can establish upper bounds on the magnitude of the effects. If the very large input changes produce large effects, subsequent sets of integrations can be carried out with smaller input changes; but if only small or negligible effects are produced by large input changes, we may conclude that much smaller input changes would have even smaller effects.

Accordingly, we carry out four more sets of integrations which differ from the control run only in the value of solar constant or amount of ozone. The values of solar constant employed are 2/3 and 3/2 the normal value, and the values of amount of ozone are zero and twice the normal value. The specifications of the six integrations are given in table 1.

RESULTS OF OZONE EXPERIMENTS

Figures 1 to 3 show maps of 500-mb geopotential height in a region surrounding North America at 11.5 days after the start of the integrations. The upper maps shown in each case are for the various perturbation experiments (PREDIC, OZ = 0, and OZ = 2), while the lower map is for the control experiment (OZ = 1) and is the same in each of the figures. OZ is the ratio of the amount of ozone to the standard amount. It is clear that the map least resembling the control run is that of the predictability run. The changes in the amount of ozone apparently produce no effect above the noise level of natural variability of the model, as measured by the difference between control and predictability runs.

TABLE 1.—*Specifications of Integrations*

Name of run	Initial state	Normalized solar constant	Normalized amount of ozone
Control (also called $S=1$ or OZ=1)	Standard (0000z GMT December 20, 1972)	1	1
Predictability (PREDIC)	Perturbed (see text)	1	1
OZ=0	Standard	1	0
OZ=2	Standard	1	2
$S=2/3$	Standard	2/3	1
$S=3/2$	Standard	3/2	1

Figures 4 to 7 show the time evolution of the global integrals of the four basic forms of atmospheric energy, for the same four integrations. Again, the changes in the amount of ozone give no significant effect.

Table 2 compares the time evolution, for the four integrations, of global atmospheric temperature, mean temperature in the highest model layer, mean temperature in the lowest model layer, and global cloud cover. Only in the highest layer (centered at about 65 mb) do the changes in the amount of ozone have a significant effect.

RESULTS OF SOLAR CONSTANT EXPERIMENTS

Figures 8 to 10 are the 500-mb maps for the three experiments (PREDIC, $S = 2/3$, $S = 3/2$) compared with the control run ($S = 1$) in a format similar to that of figures 1 to 3, but at 8 days after the start of the integrations. S is the ratio of the solar constant to the standard value. The effect of the solar constant changes appears insignificant, although significant changes do occur after 8 days.

Figures 11 to 14 display the time evolution of the four energy integrals for the four cases. These do show an effect, principally in zonal, available, potential energy (fig. 11), essentially a measure of the pole-equator temperature gradient. It must be borne in mind, however, that this effect is in response to unrealistically large changes in solar constant. The small effects of these changes on mean atmospheric temperature and cloud cover are shown in table 3. A search for ground temperature changes at selected grid points produced none that stood out over the noise due to natural variations in weather.

DISCUSSION AND CONCLUSIONS

In interpreting these results, it is useful to note that the planetary blackbody equivalent tempera-

TABLE 2.—*Temperatures and Cloud Cover in the Ozone Experiments*

Variable	Run	Days 1 to 3	Days 4 to 6	Days 7 to 9	Days 10 to 12
Mean global atmospheric temperature, °C	OZ=1	−26.06	−26.73	−27.23	−27.49
	PREDIC	−26.06	−26.71	−27.21	−27.43
	OZ=0	−26.17	−27.10	−27.47	−27.78
	OZ=2	−25.97	−26.54	−26.71	−27.02
Mean temperature in highest model layer, °C	OZ=1	−58.58	−59.10	−59.26	−59.44
	PREDIC	−58.61	−59.09	−59.26	−59.51
	OZ=0	−60.80	−59.23	−61.91	−62.97
	OZ=2	−58.08	−57.45	−56.65	−55.95
Mean temperature in lowest model layer, °C	OZ=1	2.82	2.21	1.91	1.63
	PREDIC	2.48	2.11	1.81	1.37
	OZ=0	2.79	2.14	1.87	1.63
	OZ=2	2.82	2.20	1.63	1.65
Mean global cloud cover, percent	OZ=1	33	46	49	48
	PREDIC	33	46	49	48
	OZ=0	33	46	49	48
	OZ=2	33	46	49	48

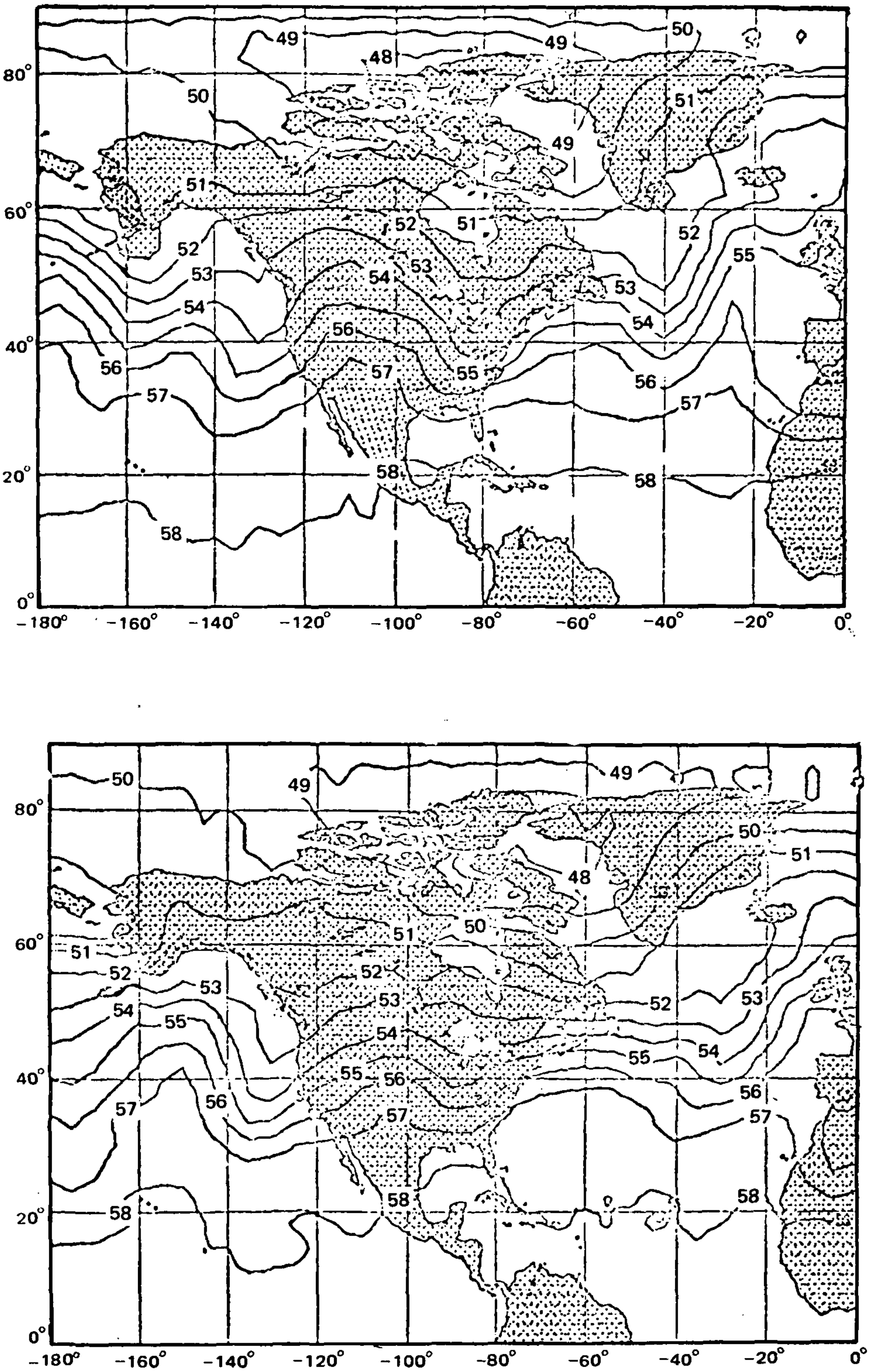

FIGURE 1.—500-millibar maps at 11.5 days. Numbers on map in figures 1 to 3 and 8 to 10 represent height of 500-millibar level in 100 m. *Upper:* PREDIC; *lower:* control (OZ=1).

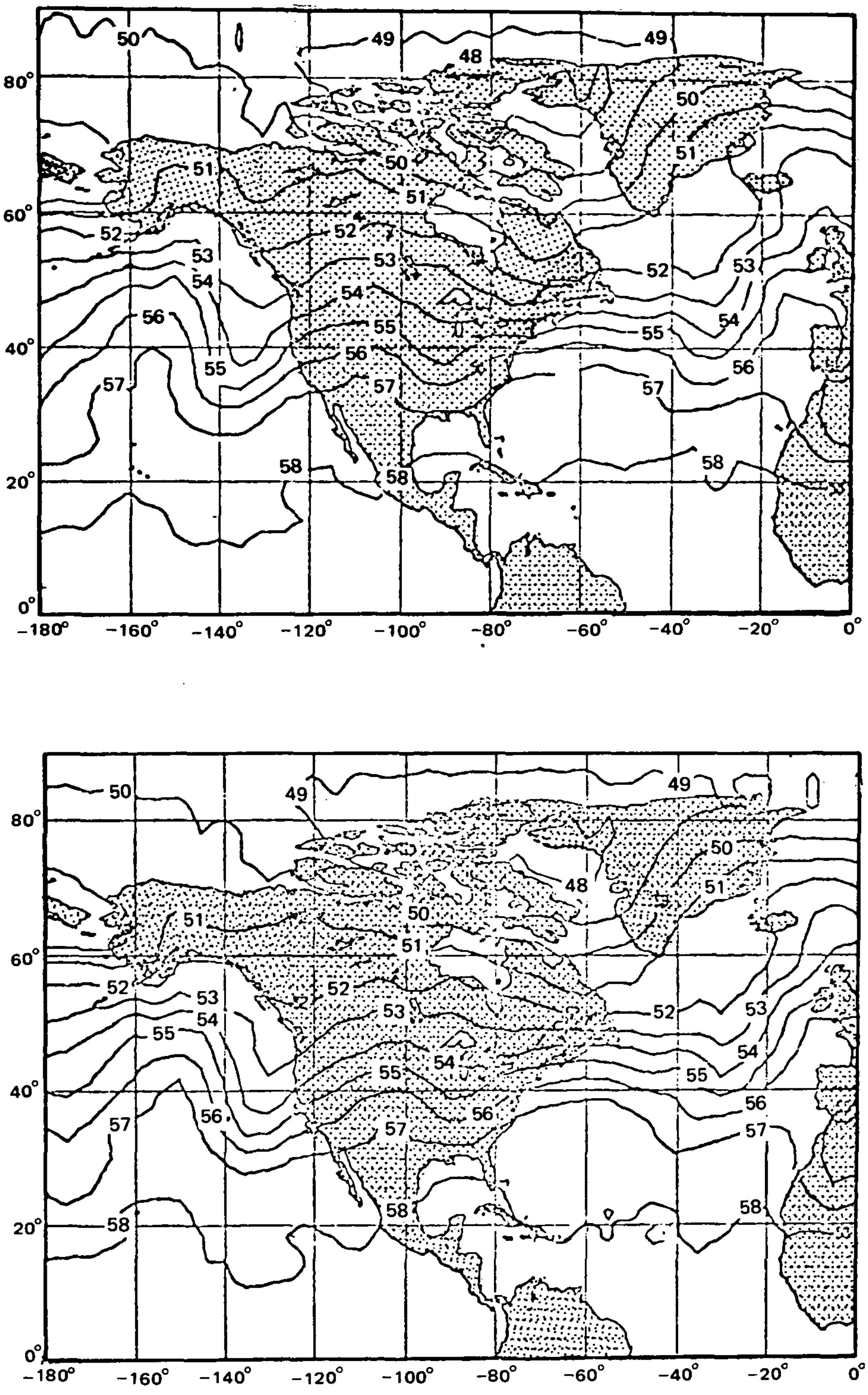

FIGURE 2.—500-millibar maps at 11.5 days. *Upper:* OZ=0; *lower:* OZ=1.

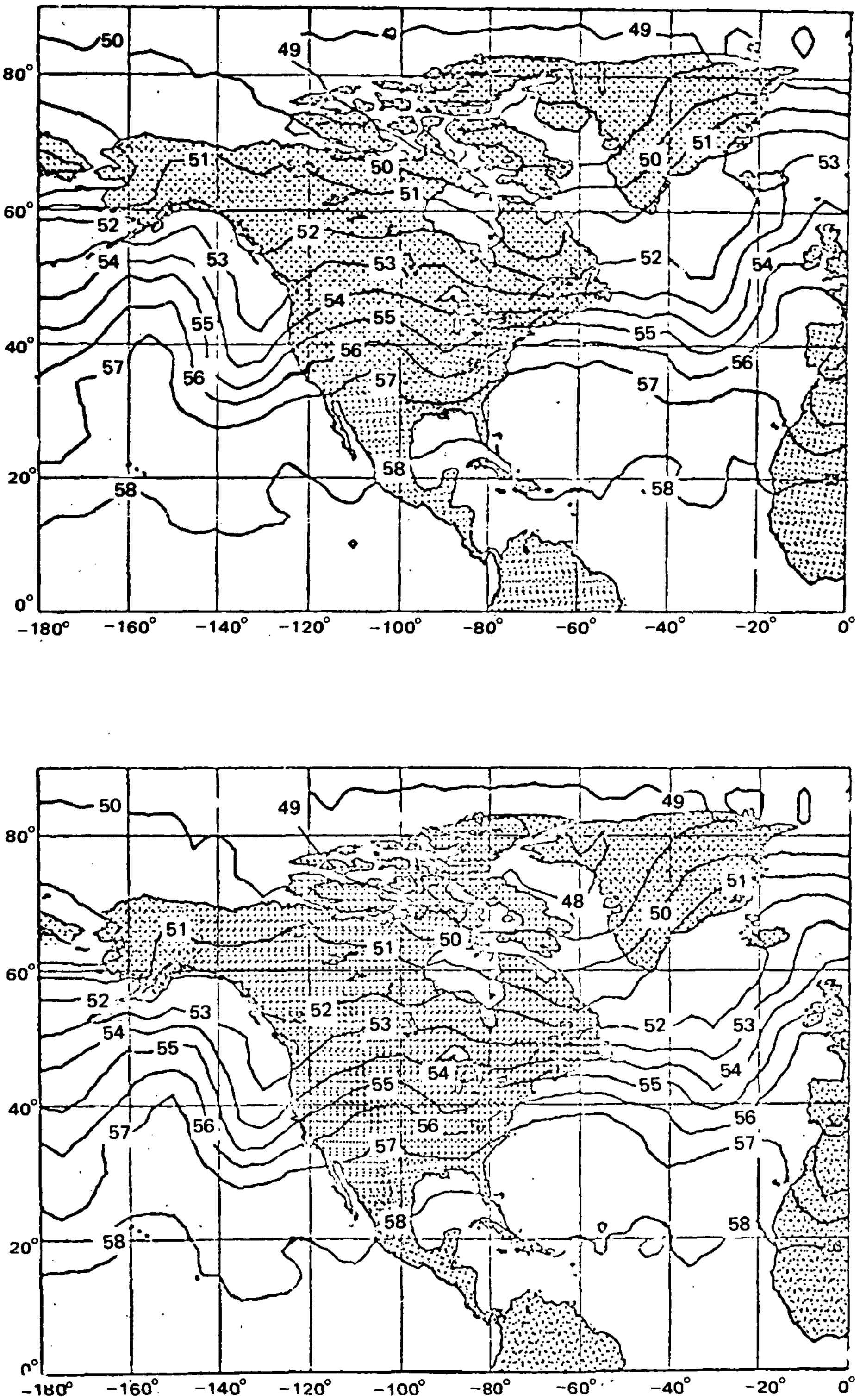

FIGURE 3.—500-millibar maps at 11.5 days. *Upper:* OZ=2; *lower:* OZ=1.

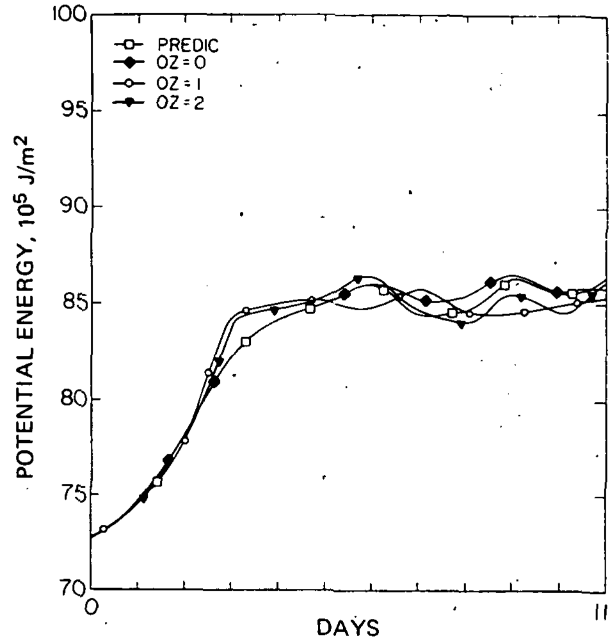

FIGURE 4.—Time evolution of globally integrated, zonal, available potential energy (PM) for the ozone experiments.

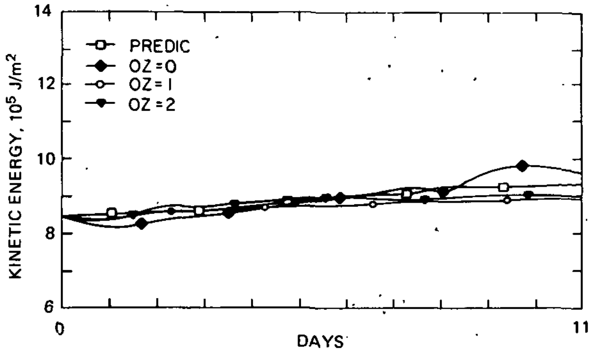

FIGURE 5.—Time evolution of globally integrated, zonal, kinetic energy (KM) for the ozone experiments.

ture (BBET) is proportional to the fourth root of the solar constant, so that a change of about 50 percent in solar constant should produce a change of about 10 percent, or about 25 K, in BBET. In our experiments, we would expect much smaller temperature changes, both because the model's sea-surface temperature is fixed and because the integrations are short compared to the tropospheric radiative relaxation (*e*-folding) time of about 50 days (Goody, 1964, table 9.3).

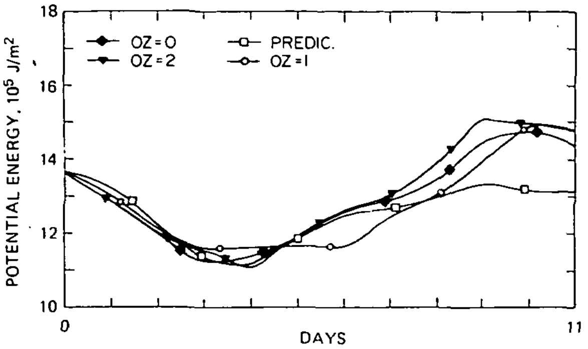

FIGURE 6.—Time evolution of globally integrated, eddy, available potential energy (PE) for the ozone experiments.

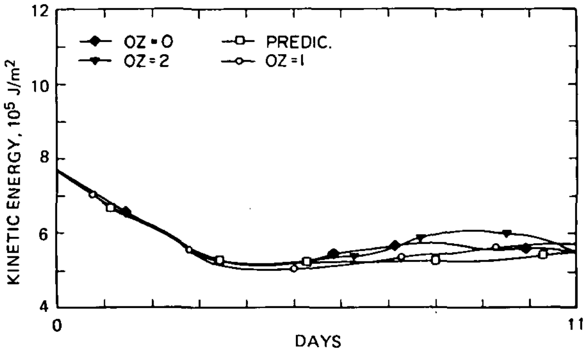

FIGURE 7.—Time evolution of globally integrated, eddy, kinetic energy (KE) for the ozone experiments.

This 50-day time scale cannot be greatly reduced by invoking additional heat transfer mechanisms. Both the approach to radiative-convective equilibrium (Manabe and Wetherald, 1967) and the effects of large-scale eddies (Stone, 1972) involve time scales of about 30 days, a number consistent with the equilibration time scale of general circulation models (for example, Manabe et al., 1965).

This expectation of small temperature changes is in fact borne out by our results. (See tables 2 and 3.) The largest changes in global temperature, 2.4 K, occur in the run with increased solar constant, but even here the change is small compared to 25 K and compared to the natural variability of temperatures in typical weather patterns. Thus our negative results are theoretically plausible. We conclude that any causal relationship between solar variability and terrestrial

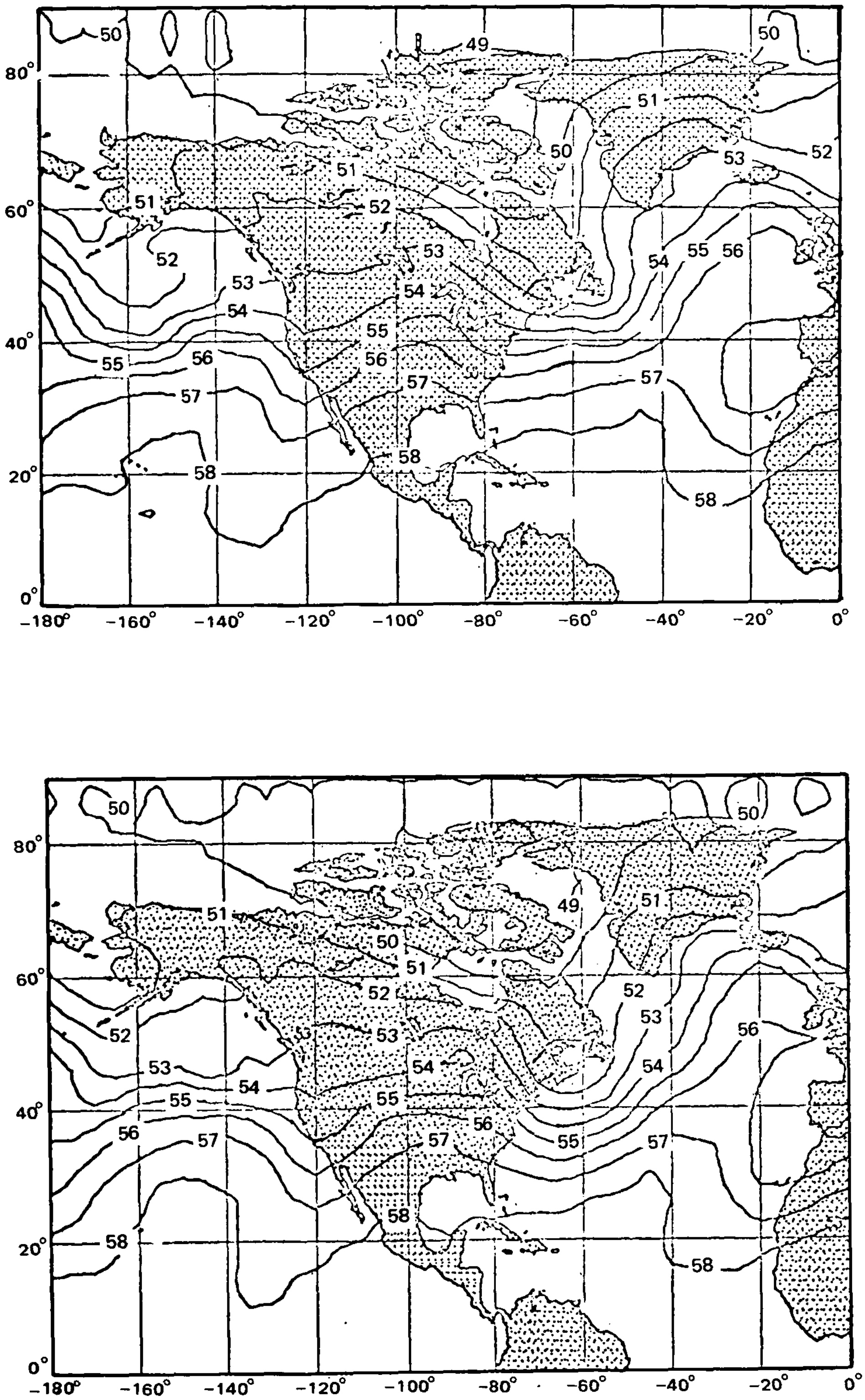

FIGURE 8.—500-millibar maps at 8 days. *Upper:* PREDIC; *lower:* (S=1).

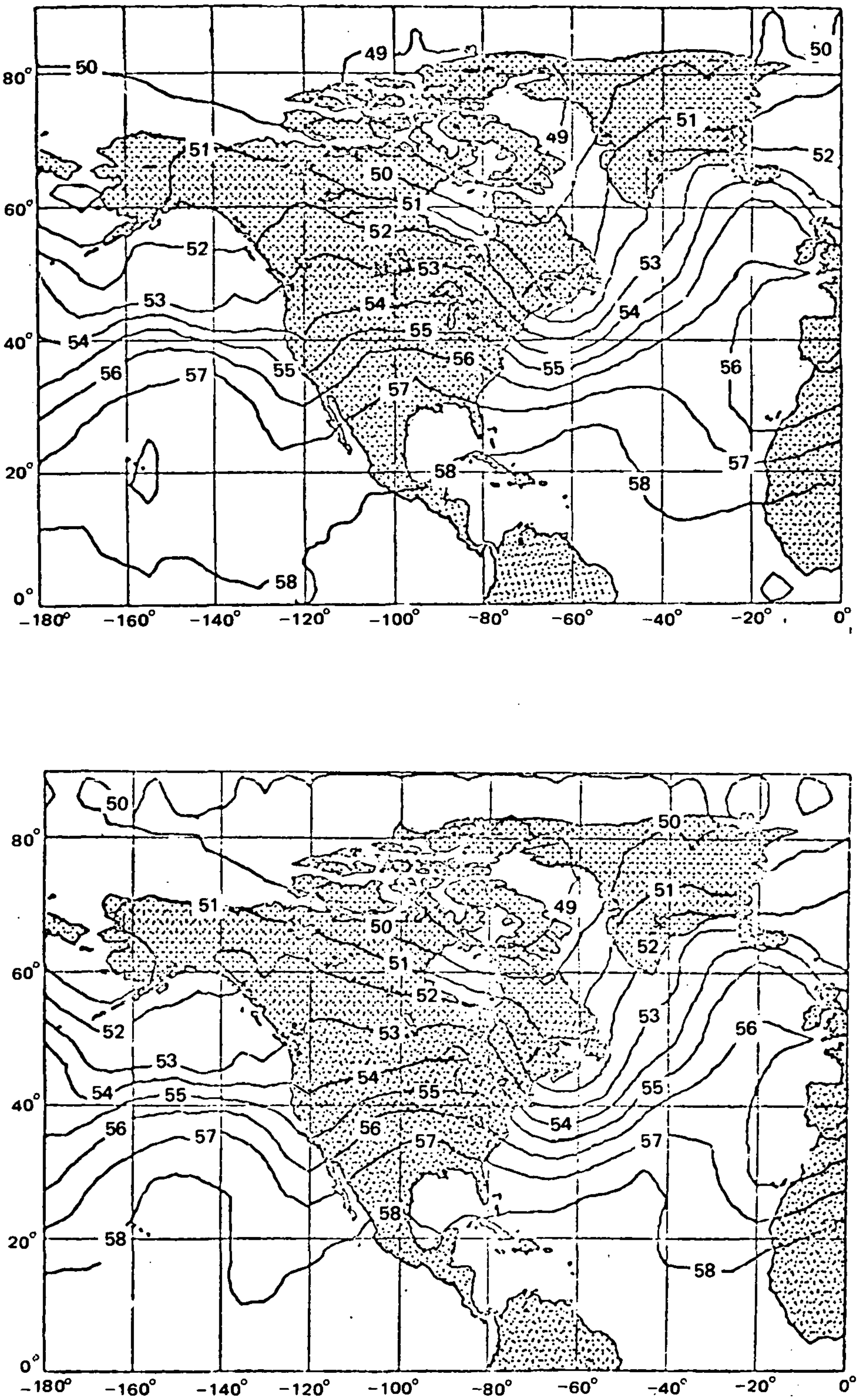

FIGURE 9.—500-millibar maps at 8 days. *Upper:* S=2/3; *lower:* S=1.

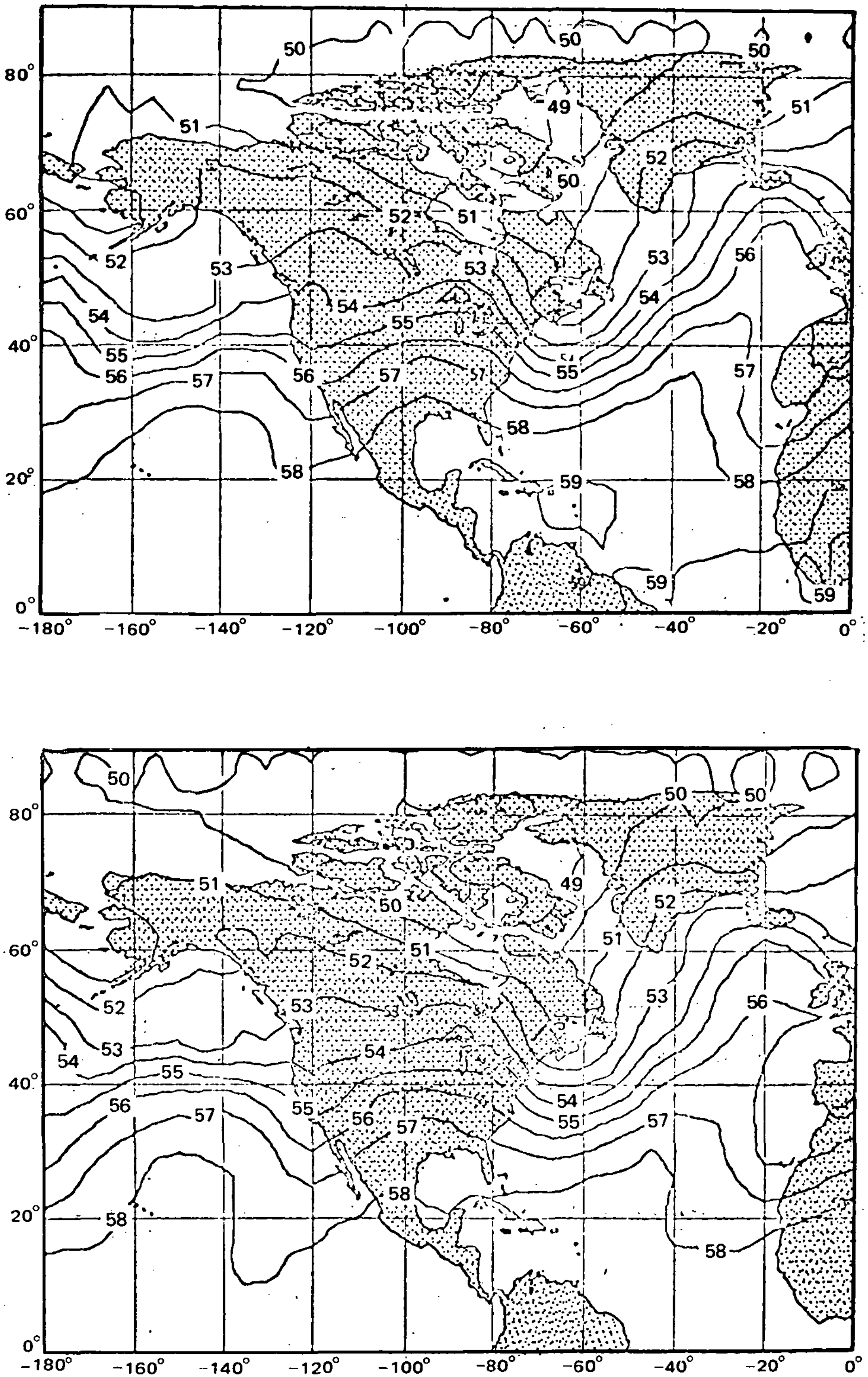

FIGURE 10.—50-millibar maps at 8 days. *Upper:* S=3/2; *lower:* S=1.

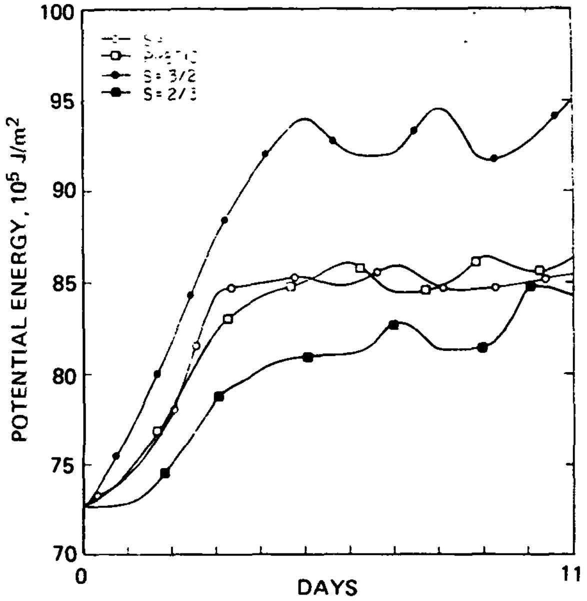

FIGURE 11.—Time evolution of globally integrated, zonal, available potential energy (PM) for the solar constant experiments.

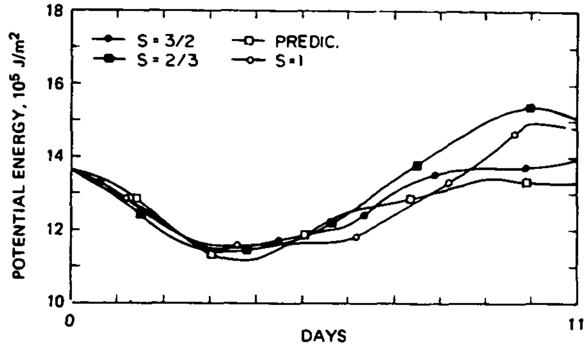

FIGURE 13.—Time evolution of globally integrated, eddy, available potential energy (PE) for the solar constant experiments.

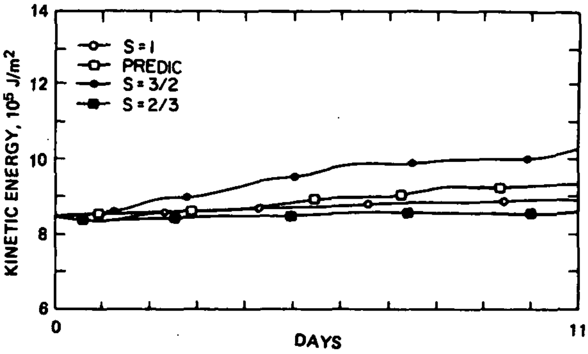

FIGURE 12.—Time evolution of globally integrated, zonal, kinetic energy (KM) for the solar constant experiments.

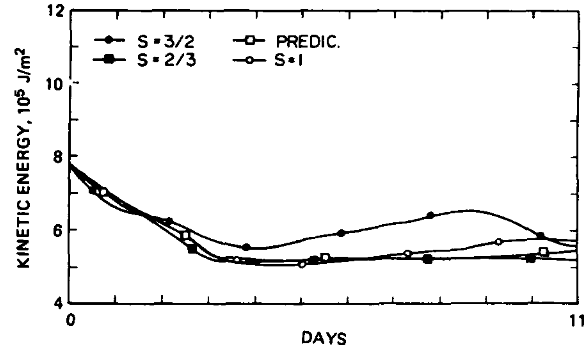

FIGURE 14.—Time evolution of globally integrated, eddy, kinetic energy (KE) for the solar constant experiments.

TABLE 3.—*Temperature and Cloud Cover in the Solar Constant Experiments*

Variable	Run	Days 1 to 3	Days 4 to 6	Days 7 to 9	Days 10 to 12
Mean global atmospheric temperature, °C	$S=1$	−26.06	−26.73	−27.23	−27.49
	PREDIC	−26.06	−26.71	−27.21	−27.43
	$S=2/3$	−26.46	−27.72	−28.74	−29.02
	$S=3/2$	−25.65	−25.50	−25.22	−25.13
Mean global cloud cover, percent	$S=1$	33	46	49	48
	PREDIC	33	46	49	48
	$S=2/3$	34	46	49	48
	$S=3/2$	33	46	49	48

weather on time scales of two weeks or less will have to rely on changes in parameters other than solar constant or ozone amount, or on mechanisms not yet incorporated in our model.

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DISCUSSION

QUESTION: If you remove the ozone, what does happen physically—does the UV deposition height go down, or the temperature change, or what happens to the model when you do not have the top layer?

SOMERVILLE: I think what you are essentially changing is the stability—this is speculative—but you are changing the stability near the top of the model atmosphere by simply having a temperature change in the uppermost layer.

MARAN: I think the ozone results are interesting. However, the solar constant variations considered were on time scales on which you do not expect changes of the magnitude considered. It would be very interesting to apply this method to the long time scales that Cameron discussed. When you are changing the solar constant, do you mean that you are essentially changing the visible and near visible light?

SOMERVILLE: Yes. There is certainly no simple accounting, as I said earlier, of the particle flux or any other aspect, of the electromagnetic radiation. And you are quite right, you would not expect large changes of the solar constant on these time scales. On the other hand, there are coupling mechanisms in the model atmosphere that are, in some ways, as complicated and well hidden as those in the Earth's atmosphere. So it is nice to have that preconception confirmed. The other point I would like to make is that we do agree that it would be important to make those observations using longer time scales, but obviously it is necessary to run for a short time before you run for a long time.

WILCOX: Would it be possible to introduce the following kind of perturbation into your model? They can recognize this curve. (Dr. Wilcox sketched on the blackboard a curve from figure 2 of his paper.) We know that, on the average, the vorticity area index had this kind of behavior averaged over the northern hemisphere so that, say, when you started on December 20, it might be interesting to try to introduce this perturbation when the next boundary came by. How would we want to do that? We know that it is kind of a hemispheric effect. It is not particularly localized to any one area, so that you might change conditions somehow, for example in every trough that you have, so that it went through this behavior. The magnitude is about 10 percent on the average. Would it be feasible to make an alteration like that?

SOMERVILLE: Yes, you can tinker with model fields any time you want. I am not sure what your goal is, what you would be learning by altering the model?

WILCOX: You would compare the result of that alteration with the behavior that is actually observed and see if this result has improved over the results you obtain when you do not make the alteration.

SOMERVILLE: That comparison is certainly possible to make.

WILCOX: That procedure would begin to give you some clearer insights into what seems to be a fairly substantial solar influence on the weather, as compared with the influence of the solar constant on the ozone, which did not seem to have very much effect.

SOMERVILLE: The feasibility of the procedure, of course, would depend on the deviation with which the model atmosphere had departed from the real atmosphere, if you were verifying it with respect to the real atmosphere, by the time the effect occurred. Possibly this effect would be lost in the noise of the other effects, model deficiencies, and poor observations which degrade the quality of the forecast.

PRABHAKARA: From the description of the model you gave, there is a decoupling, a deemphasis, of the subgrid scale phenomena compared to the meteorological scales that are built into the models. Namely, increasing the solar constant by 50 percent or decreasing it by something of that order can influence the subgrid phenomena in a much more pronounced manner. Then they would have, presumably, feedback into the meteorological scale. And this feedback is inhibited in the model. If it can be promoted, one might find a direct relationship.

SOMERVILLE: I quite agree. The assumption that you have to make, which is bold but very necessary in constructing a model like this, is that everything that is important that takes place on smaller scales than those explicitly resolved by the model grid (and the gridpoints are separated by something like 400 km in middle latitudes) can be uniquely represented. There is an algorithm that defines the feedback of these small-scale processes on the large scale, given the large-scale values of the fields as explicitly calculated by the model. And that assumption, the parameterizability hypothesis, is by no means on firm ground with respect to many small-scale processes. But you have to make it if you are to run the model at all. You cannot ignore these processes; you cannot possibly compute them explicitly.

BANDEEN: I have a little difficulty when I see charts showing the cloudiness computed by the model. For example, amount of cloudiness is only part of the problem. The height of the clouds and the transmittance at various wavelengths are also important. In one of your graphs, where you showed a considerable lesser amount of cloudiness computed compared to cloudiness observed, and you stated that the clouds in the model were treated as black bodies, it occurred to me that they really were quite equivalent to the greater amount of real cloudiness.

In many cases the transmittance of the clouds in a real atmosphere is considerably, upwelling radiation from lower levels being transmitted through the clouds, inasmuch as they are not at all like black bodies. So it occurred to me that the large discrepancy that was apparent on the graph really was not that large at all, considering the other factors of real clouds.

SOMERVILLE: Yes. I think your statement might be correct. It is also true that in models like these, in which the sea surface temperature is fixed and the lapse rate is strongly constrained by the internal dynamics, such as an adiabatic bound on the lapse rate, the radiative transfer in the model atmosphere may be much less important than in the real atmosphere for determining the thermal structure of the atmosphere.

Once you fix the boundary condition on temperature, and go a long way toward fixing the slope, then you come close to fixing the temperature field. And that kind of empirical lock is going to mask the effect, in many cases, of a deficient radiative transfer treatment, whether it is in the radiative transfer itself or in the input to it such as the cloud field, so that the kind of compensation you mentioned may be present. Even if it were not, we might not notice it. This deficiency is a major problem in extending models like this to computing climates which may be very different from the present climate. The effect may not show up over the time scales of weather forecasts or even extended-range weather forecasts involving a synoptic data simulation over a few weeks. But it may be crucial if you try to compute a very different climate—and all kinds of very attractive experiments have been proposed to use these models in. For example, geologists know where the continents were a hundred million years ago, and something about the surface conditions then. You could change the boundary conditions correspondingly within a model and compute the climate of a hundred million years ago. Carrying out this kind of calculation is a high risk game right now, because of the kinds of model deficiencies that we have been discussing. But I think your point is well taken.

QUESTION: I noticed on some of your energy curves that there was a tendency for them to change during the first 4 or 5 days, and then they flattened out. What is the reason for that kind of behavior?

SOMERVILLE: The reason is that the equilibrium state of the model differs from the initial state. Whether the difference is because of observational uncertainties—we are starting from real meteorological data, which, as you know, over much of the Earth are not very reliable—or whether it is because the equilibrium state of the model is truly different from the state of the atmosphere in December of last year, it is hard to say. But you are quite correct that there is an adjustment time of a few days.

QUESTION: Does that mean that the weather, in a sense, goes away?

SOMERVILLE: In part, it does go away. Although there is degradation in the aspects of the model that are actually used in forecasting, it is not that fast. And although this model, and any other such model, in fact, produces useful forecasts only for a few tens of hours after the initial state, the model is nonetheless better than randomly correlated with the real atmosphere for even a week or more. The forecast may not be useful, but there is some resemblance left.