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SENSITIVITY OF THE EARTH'S CLIMATE TO CHANGES IN THE SOLAR CONSTANT

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ABSTRACT

A brief review of climate sensitivity to solar variations is presented with special attention to simplified models. A number of uncertainties remain in our understanding of climate and these are elaborated upon. Especially vexing are possible feedbacks which might operate on long time scales and are therefore not testable directly.

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The earth's climate is determined by the brightness of the sun, the earth orbital parameters, and the materials of the earth-atmosphere system which dispose of the sunshine by absorbing, storing, transporting and reradiating it to space. The climate system is very complex but we can be reasonably assured that the sun is the primary forcing agent that drives it. Our crude attempts to observe and model climate suggest that the mean values of such variables as temperature are very sensitive to the solar output. Hence the climatologists are very interested in obtaining an accurate history of the solar constant.

Our ability to study climate has improved significantly in recent years because of advances in many different fields. Large computers allow us to simulate the geophysical fluid motions and forecast weather with tolerable accuracy for several days. Satelites and thousands of surface observers report data continuously; the computers assimilate the data and convert it to manageable forms. The paleoclimatic record is becoming legible through the ingenious use of tree ring data, ocean bottom stratigraphy, glacial ice cores, and other indirect methods. These are accompanied by advances in applied mathematics and statistics.

Important aspects of the earth's climate remain poorly understood despite the surge in research activity over the past few years. The scientific study of the large-scale climate is hampered by our inability to test our theories. Even the astrophysicist can test his theories of remote objects because so many different ones exist. On the other hand the student of terrestrial climatology has only one earth with a rather short and spotty record of its history.

The problem of formulating a theory which is "interesting" arises. With so few data points in space-time it is not difficult to formulate a multiplicity of theories which fit the data. All theories of climate contain fudge factors which can be adjusted to bring the model output into some conformity with observations of the present climate. The question, of course, is what happens if one of the externals, such as the solar constant, is changed. This class of investigations is called sensitivity studies. My purpose here is to familiarize you with the simplest types of sensitivity estimates in the context of the model hierarchy and to point out several paradoxes which we have not been able to resolve satisfactorily. In this way I hope you can get some feeling for the state of the art of climate modeling.

The key concept in climate modeling is that of model hierarchy discussed in reference 1. The number of variables or degrees of freedom delineate the rung occupied by a particular model. The problem is that the largest models, similar to weather forecast models, have ~10^5 degrees of freedom and the numerical solution of them proceeds at a rate of about one-tenth that of nature itself. Such models are very interesting since they are the closest facsimile we have to the real climate. We can control the boundary conditions, and do various experiments with the artificial climate produced. Still only crude attempts have been made to couple these models to the oceans or cryosphere. The reason for this lack of progress has been the longer time constants associated with ocean and ice dynamics. Any model simulating these variables will have to run for decades to reach equilibrium. Hence, the large models as presently formulated are useful only when these components are taken as given. Nevertheless, many interesting experiments are possible even with these constraints. The large models are extremely useful in establishing the higher frequency (few days) feedbacks in the atmospheric part of the climate system. The developmental research for giant models is still very actively pursued because a number of problems remain in the construction of the models especially with regard to the surface (turbulent) boundary layer and the inclusion of cloudiness variability.

At the other end of the hierarchy are the models with only a few variables. These models are motivated by the most crude expressions of the conservation of energy. The study of these models was brought into vogue by Budyko and Sellers in the late sixties. Cahalan, Coakley, and I (ref. 2) recently reviewed the progress in understanding these "toy" models over the last decade. That review was written for the general reader, hence the present note will be brief.

I can illustrate the concept of sensitivity with a simple zero dimensional global energy balance model:

$$A + BT + \frac{\sigma_0}{4}(1 - \alpha_p). \qquad (1)$$

The left hand side is the outgoing infrared terrestrial radiation (Watts/m^2), with T the globally averaged temperature, A and B are empirical coefficients estimated from satellite data. The solar constant is σ_0 ($\approx$1380 W/m^2), α_p is the albedo averaged over the globe and weighted by the average fraction of sunlight reaching each latitude band; the factor of four comes from the ratio of sphere to disk area.

Consider a change in solar constant $\Delta\sigma_0$. If α_p is fixed, the change induced in T will be given by

$$\frac{\Delta T}{(\Delta\sigma_0/\sigma_0)} \approx \frac{\sigma_0}{4B}(1-\alpha_p)$$

The sensitivity β_o is defined as this number divided by 100, i.e. the number of degrees of change for a one percent change in solar constant. If A and B are estimated for a black body radiator we obtain (B $\simeq$ 4.6)

$$\beta_o \sim 0.60^\circ K$$

Black
radiator

On the other hand if B is estimated from satellite data we find that B ~ 2.0W/(m^2deg), and the sensitivity increases to about twice that of the black body radiator. The reason for this doubling of the sensitivity is the so called "water vapor feedback".

$$\beta_o \sim 1.20^\circ K$$

water
vapor

The mechanism responsible is connected with the empirical fact that when surface temperatures increase, the relative humidity tends to stay fixed while absolute humidities increase, thereby increasing the absorption of infrared radiation in the atmosphere. This increased greenhouse effect leads to an amplified response of the surface temperature--hence the term "positive feedback". We have confidence in our estimate of the magnitude of the water vapor feedback since its effect is almost instantaneous (therefore testable with very detailed models) and the physics is confined to radiative transfer (well understood). The net effect is simply a halving of B and therefore a doubling of β_o.

A more peculiar feedback mechanism is the ice-albedo effect. Suppose α_p is a function of temperature such that for T small α_p is large (large fraction of earth ice covered) and vice-versa. Fig. 1 shows a graph of the left and right hand sides of eq. (1); intersections of the graphs indicate equilibrium climate solutions. The warmest climate (~15°C), root I, corresponds to the present situation. Root III is a completely ice-covered planet, and root II is an unstable intermediate solution of no physical significance. If the solar constant is lowered, roots I and II approach each other, finally merging and disappearing leading to only the deep freeze root, III. Fig. 2 shows the global temperature as function of the solar constant, as computed from Fig. 1. It is remarkable that such a simple model can exhibit so rich a solution structure. The literature over the last few years (see, for example, ref. 2) has revealed study after study up and down the model hierarchy all of whose members have this same multiple solution property due to the nonlinear ice-albedo feedback. Even the most complicated models, however, still parameterize the deposit of snow and ice in essentially the same way. No models ask about the availability of enough moisture to ice over the earth, for example.

Here we are led to the so-called Faint Sun Paradox discussed by many authors (for example, ref. 3 and 4): since fundamental astrophysical considerations suggest that the luminosity of the sun has increased monotonically from around 70 percent of its present value, we see from Fig. 2 that the earth should still be iced over. It is not iced over (!) and geological evidence suggests that it never was. The favorite way out of this dilemma is to speculate that in the past the atmospheric composition was very different with more greenhouse constituents preventing the ice over (for example, ref. 5). I find this argument very unconvincing since it requires the invocation of a rather improbable scenario. Unlike the astrophysical arguments leading to the increase of solar luminosity, it is not very "robust" regarding its dependence upon detailed assumptions that are untestable. I suggest that the explanation lies in the way ice distributes itself even on a very cold planet. In any case we are not ready to trust climate models as presently formulated under conditions more than infinitesmally different from those at present nor over such long time scales where totally new feedbacks such as geochemistry may come into play.

The presently accepted value of the sensitivity to solar constant changes is in the range 1.5 - 2.0°C. This figure is to be compared with the value 2.0 - 3.0°C change estimated for doubling the CO_2 content of the air. Most models suggest that the thermal response is latitude dependent, increasing toward the poles. Even small changes in the global temperature can be accompanied by large local effects due to the shift of climatological zones. The great plains region of the United States is such a sensitive zone.

Finally I would like to aquaint you with another paradox with conventional climate models (large and small). Geological evidence suggests that over the last few million years there have been numerous advances and retreats of the continental glaciers on time scales of thousands of years. The period before that was ice-free and possibly 5-10°C warmer than now. The continents were in a different configuration in those days and presumably their positions now are more favorable for the cooler, more variable climate. Small climate models have been subjected to such changes in their surface boundaries and they do not yield global temperatures more than a degree or two different from the present. I suspect the same result applies up and down the hierarchy. (Thompson, Barron and Schneider reported this result as the First Conference on Climate Variations, San Diego, Jan. 1981.)

A supporting and probably equivalent paradox is related to the glacial advances and retreats that have occured over the last few million years during the recent cool period. These great waxings and wanings of the continental ice sheets appear to be in step with the changes in the earth's orbital elements (eccentricity, obliquity, and phase of perihelion) (ref. 6) on the time scale of 10^4 - 10^5 years. Again, simple climate models (ref. 2) fail to give the required responses by at least a factor of five.

It is almost certain that the large models will replicate this result, since the energy balance models are "tuned" to give the correct amplitude of the seasonal cycle and have the same overall sensitivity as the giant models.

These latest paradoxes suggest to me that low frequency feedbacks are playing a very significant role in amplifying climate response to energy budget perturbations. This problem will not be solved by improving the atmospheric component of giant models. The problem is likely to reside deep in the oceangeology system and may even involve geochemistry. Less hopeless possibilities involve the biosphere. These low-frequency feedbacks are very difficult to incorporate in our climate models, because we have no way to calibrate (fudge) the inevitable unknown coefficients. If a single coefficient is left to guesswork the whole answer is left uncertain.

If our models disagree with paleoclimatology by an order of magnitude, where do we stand on the other questions of current interest such as the doubling of CO_2 which is likely to occur in the next 50 years? I wish to emphasize that the "unknown" low frequency feedback may operate on time scales as short as decades since our closest test is the seasonal cycle.

I have tried in the foregoing to assess the current level of uncertainty in climate modeling. It is clear that we have lots of work to do to bring the data and the models together. It would be especially useful if we could ask nature to change the solar constant at different frequencies for us so we could measure the response. Remember that the system is very noisy so that we need lots of cycles (at each frequency). A similar "natural" experiment can be done with volcanoes and the dust they leave in the stratosphere. Again we need lots of them with accurate estimates of their optical effects. My guess is that there is no substitute for monitoring and waiting.

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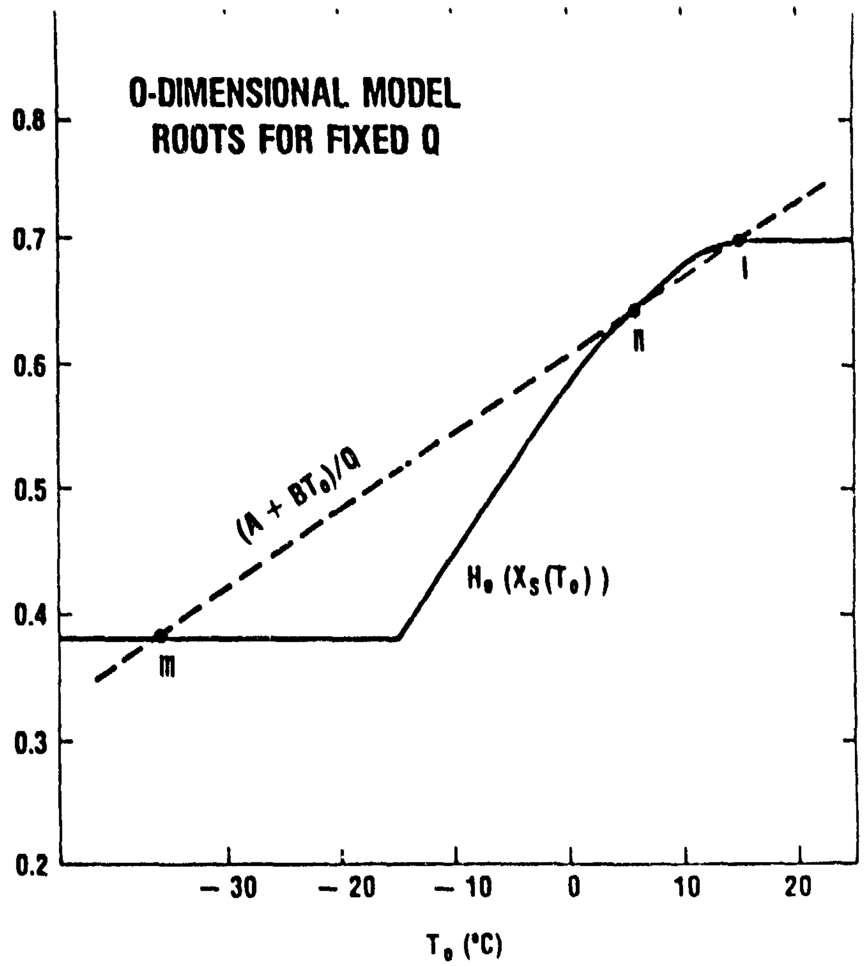

Figure 1. Fraction of solar radiation absorbed (solid curve), depicted here as $H_0(x_S(T_0))$ but in the present paper $(1-\alpha p)$. The dashed curve shows the left-hand side of Equation 1 with $Q = \sigma_0/4$. The three roots are described in the text. (from Ref. 2)

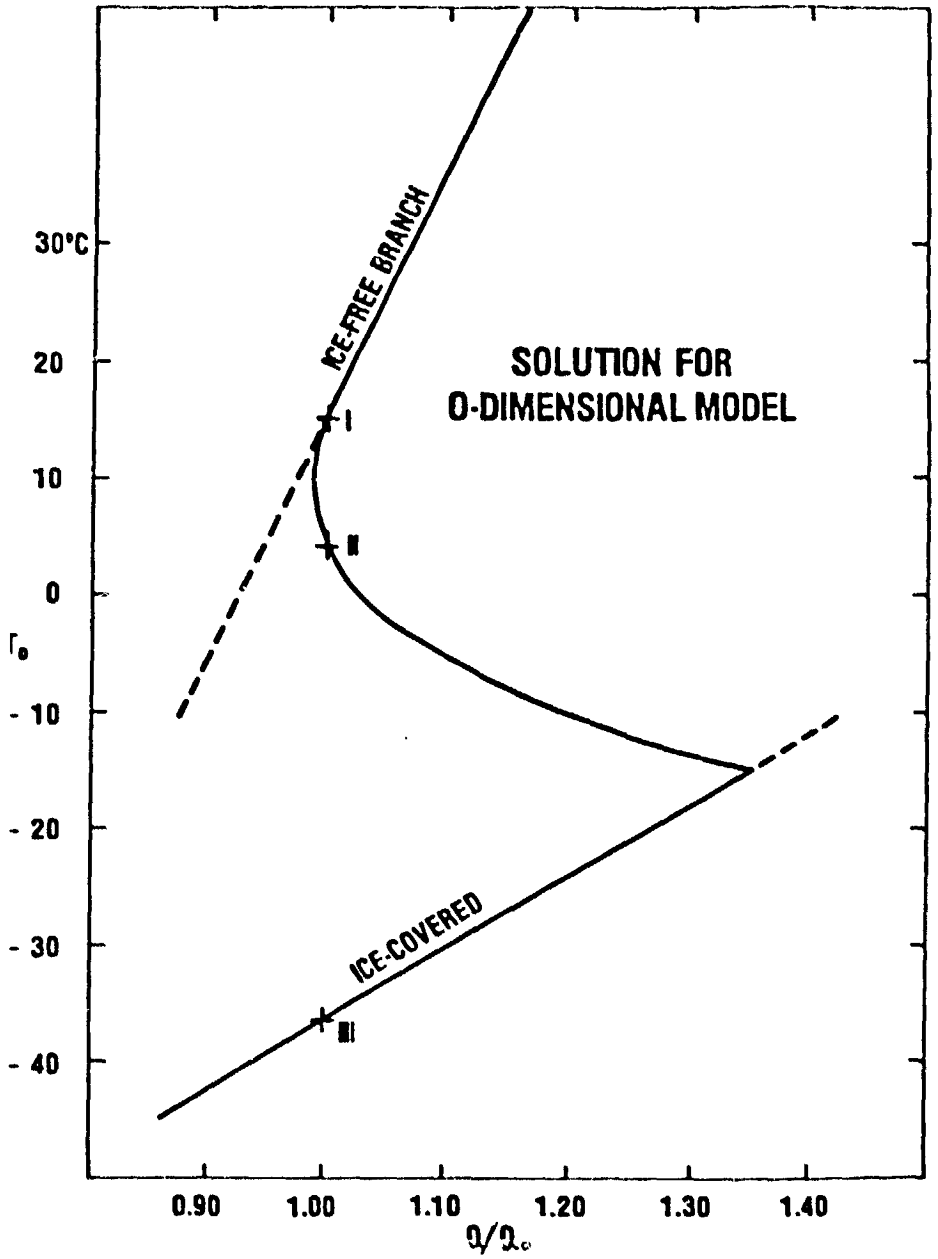

Figure 2. Steady state temperatures corresponding to solutions in Equation 1 or Figure 1 for different solar input Q/Qo (Qo is the present Q). The roots, I, II, III are the same as in Figure 1.