Numerical Climatic-Change Experiments: The Effect of Man's Production of Thermal Energy

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ABSTRACT

We describe in this paper a set of general circulation model experiments on possible climatic changes caused by man's generation of thermal energy or pollution. Three experiments were carried out: one in which we introduced only a small initial error, one in which we added the expected ultimate levels of thermal energy generation, and one in which we added a *negative* amount of thermal energy. In all three experiments, we obtained the same results, indicating that the thermal pollution effect is probably small compared to the natural fluctuations of the model. We also discuss some limitations of the present model for inferring the proper climatic-change response.

1. Introduction

One of the ways man may be changing his environment is in adding thermal energy to the earth-atmosphere system. It has been proposed that this additional thermal energy (sometimes called thermal pollution) could lead to a significant climatic change. We describe the results of several thermal energy experiments with the NCAR general circulation model (GCM). It is hoped that these experiments will not only shed some light on the significance of additional thermal energy on the energy budget of the earth-atmosphere, but will also indicate some of the difficulties in performing climatic-change experiments.

These experiments should not be looked upon as an investigation of the urban heat effect on the global scale because we will not take into account the radiative and surface roughness changes caused by urbanization. We shall consider only the possible effects of heat generation on climatic change. Except for studies by Budyko (1969) and Sellers (1969), there has been relatively little research on the possible modification of global climate. In the above studies, the investigations were carried out with simplified steady-state heat-balance models where the feedbacks are parameterized. Budyko and Sellers concluded that given sufficient additional thermal energy (about 5% of solar constant), the climate would be markedly different; however, the amount of thermal heat they added is much larger than that estimated by Weinberg and Hammond (1970).

Because of the expected increase in population and industrialization throughout the world, it is logical to predict an increase in man's energy production. One method of studying this problem is with a computer simulation model of the atmosphere. The present computer models are capable of simulating many major features of atmospheric circulation. For details on two advanced versions of computer models under development, we refer the reader to Holloway and Manabe (1971) and Kasahara and Washington (1971).

In a previous paper by Washington (1971), an extremely large amount of thermal energy (global total 2.5×10^{12} kW) was added uniformly over all non-ocean areas. The changes in surface temperatures that resulted from this earlier experiment were up to 1–2C in the tropics and 8C over the northern parts of Asia and North America. The reason for a larger response in the far north was because the experiment was for January when the incident solar flux at the surface is quite small compared to flux of thermal energy in those latitudes. In collaboration with S. R. Hanna of the National Oceanic and Atmospheric Administration (NOAA) and B. P. Hammond of Oak Ridge National Laboratory (ORNL), who have supplied us with a geographical distribution of thermal energy production based on population density, we have since rerun a thermal energy experiment with a more realistic distribution of expected ultimate levels of man's thermal energy production. The results of this newer experiment and others will be described.

Finally, we must emphasize that atmospheric computer models are constantly under development to improve their fidelity to the atmosphere. Therefore, climatic-change experiments of this kind should be repeated from time to time to have the best estimate of possible climatic effects and to determine the sensi-

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tivity of the results to the particular model used. Also, to investigate long-term effects of man's thermal energy production, we should repeat these experiments with a coupled atmosphere-ocean model which will allow for ocean temperature changes.

2. Discussion of model climatic variations and fluctuations

We first describe experiments to determine the natural fluctuations within the NCAR model. To understand later experiments on thermal energy, we point out the problem of sampling. Due to the computer time involved in performing these types of experiments, we are forced, unfortunately, to a small number of experiments. Given such a small sample of experiments, we must determine if the differences are due to the additional thermal energy rather than sampling difficulties. To shed light on this question and to determine the natural model variations, we conducted two experiments with identical physics. In one—the random error experiment—we added a small random initial error to the 13.5-km winds with a maximum amplitude of 1 m sec^{-1} on Day 30. The other—the control experiment—contains no initial error. The location and amount of the error are not very important, as shown by Williamson and Kasahara (1971), because the error quickly spreads and grows rapidly in local regions, particularly in the highest allowable wavenumbers. This error can be interpreted as starting the model with a slightly modified initial state. The root-mean-square (rms) global temperature error or difference between the two experiments is plotted as a function of time in Fig. 1. We see that the difference grows rapidly from Day 30 to Day 45 and then grows more slowly from Days 45–57. After Day 57, the difference between the two cases is nearly constant, indicating that the two experiments have reached their maximum deviation from each other. If we compute 30-day mean difference maps of temperature between the two experiments for Days 51–80, we find in Fig. 2 geographical differences on the order of 10C at 1.5 km. This does not mean that the climate in the two experiments is different, but that the atmosphere is capable of evolving in a somewhat different manner with essentially the same climate. By climate, we mean the long-term statistics of the flow which includes in its definition the time means and measures of the fluctuations. It is to be expected that the atmosphere and its complex models have natural fluctuations which are part of the definition of climate. Although we did not show it here, the zonal distribution of, say, temperature in the control and random error experiments is almost identical. It might be instructive to mention that Lorenz (1968, 1970) defined this behavior of the climate as *transitive*. By *transitive* he meant a climate having a single set of statistics associated with one system of equations, whereas an *intransitive* climate would have many sets of statistics associated with a single system of equations. An *almost intransitive* system would have different sets of statistics depending on the time interval of averaging chosen. Therefore, it is possible that the effects of the initial conditions influence the "climate" found with a particular set of statistics. Our experiments show that

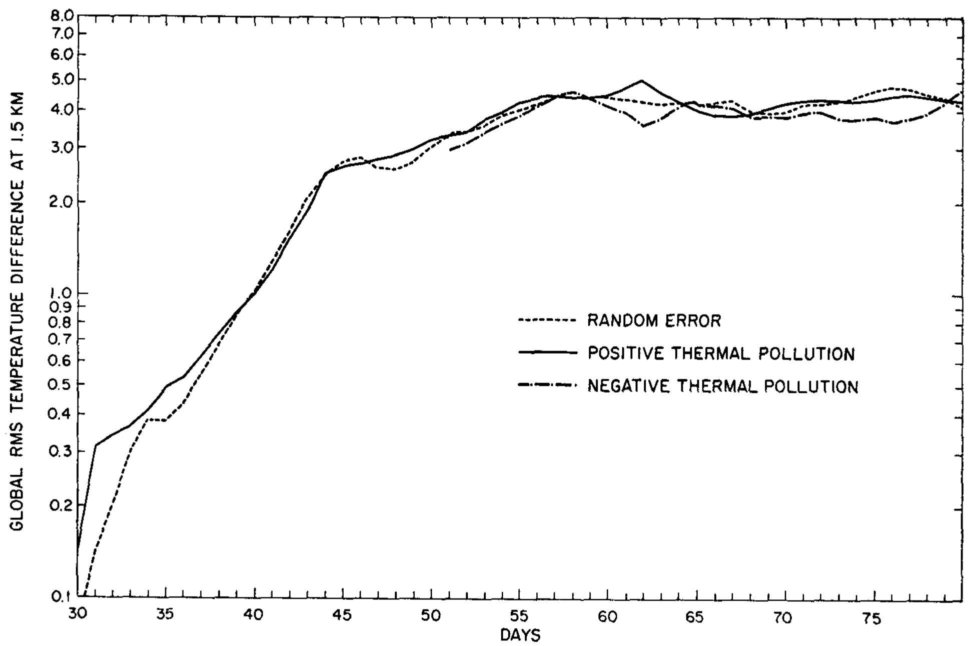

FIG. 1. Time change of global rms temperature difference at 1.5 km between control and random initial error experiment (dashed line), control and positive thermal pollution experiment (solid line), and control and negative thermal pollution experiment (dashed-dotted line).

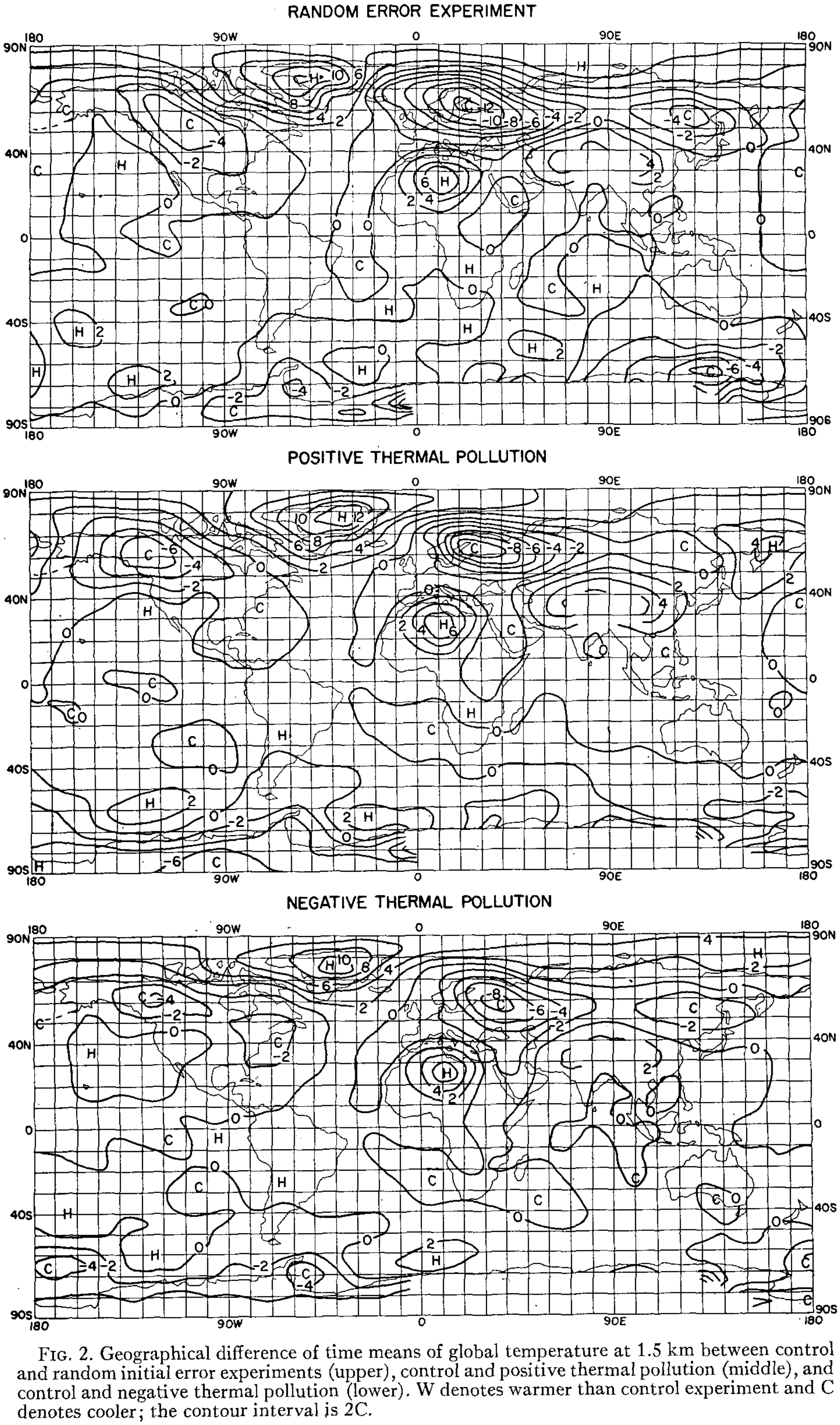

FIG. 2. Geographical difference of time means of global temperature at 1.5 km between control and random initial error experiments (upper), control and positive thermal pollution (middle), and control and negative thermal pollution (lower). W denotes warmer than control experiment and C denotes cooler; the contour interval is 2C.

if we slightly change either the initial conditions or boundary conditions[2] by adding thermal energy, the "model" climate is *essentially transitive*, i.e., the statistics change only a little.

[2] A small change in boundary conditions causes a small error in the forecasted variables after the first time step. This is essentially the same as starting the experiment with a small initial error.

3. Thermal energy experiments

The experiments described in this section are similar to a previous experiment carried out by Washington (1971) where a uniform energy flux of 50 ly day^{-1} was added to all non-ocean areas. In this earlier January experiment, over Canada and North Asia the mean monthly surface temperature rose by 8–10C within 20 days. Since the additional flux is more than 100 times the present level of man's thermal energy production and more than 6 times the expected ultimate level, this should be classified as an extreme climate modification experiment.

We have performed more realistic experiments taking into account non-uniform distribution due to metropolitan clustering and a better estimate of the thermal pollution energy flux. Weinberg and Hammond (1970) predicted an ultimate global energy input of about 3×10^{14} W, based on 15 kW per person and an ultimate population of 20 billion. This total input is about a factor of 6 less than the total input used in Washington (1971). If we assume that the 3×10^{14} W are geographically distributed in the same proportion as the present population, we then obtain the distribution shown in Fig. 3. One million megawatts averaged over a 5° latitude-longitude square in mid-latitudes are equivalent to an energy flux of approximately 12.9 ly day^{-1}. The maximum energy flux is 78 ly day^{-1}, although most land areas have fluxes much less than 12.9 ly day^{-1}. It should be noted that even the 78 ly day^{-1} is a relatively small energy flux in the tropical region compared to the incident solar flux which is typically about 500–1000 ly day^{-1}.

We added the thermal energy flux to the model continuously from Day 30 and ran the experiment out to Day 80. We then computed the means of the experiments with and without thermal energy from Days 51–80. This averaging period is consistent with results of Fig. 1. where we see that the model comes to a new quasi-equilibrium 20 days after adding the thermal energy. The rms global temperature difference at 1.5 km between the control and thermal energy experiment is plotted as a function of time on Fig. 1. We see that the thermal energy experiment reaches approximately the same equilibrium as the random error experiment, suggesting that the additional heat flux causes the model to forecast a slightly different state than was forecast without the additional heat flux. The difference between the two states is very small initially; however, once formed, the difference grows by nonlinear interactions just as in the error growth experiment. Fig. 2 shows the geographical distribution and the difference between the monthly means of the two experiments. When this figure is compared to that shown in the first part of Fig. 2, we note that even though the extrema are in somewhat different positions, the magnitude of extrema of the two figures is roughly the same. To be certain that effects of additional thermal energy are small compared to the natural variation of the model, we carried out a third experiment in which we added *negative* thermal energy. The geographical difference

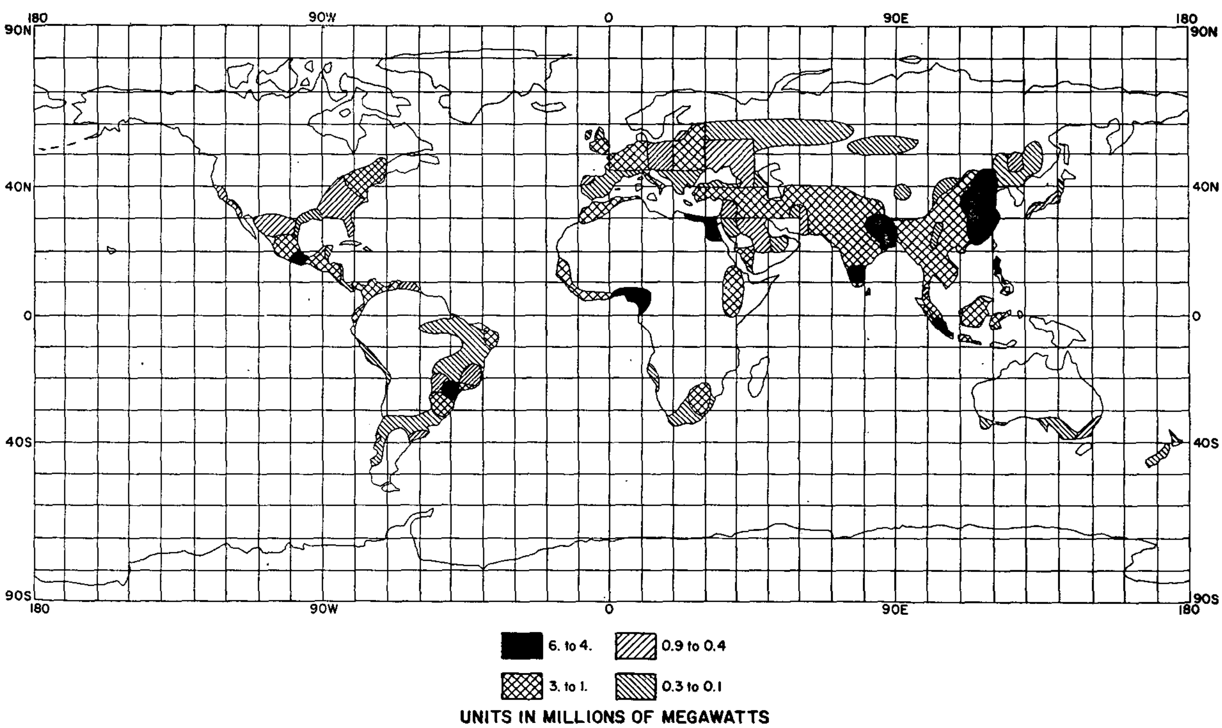

FIG. 3. Geographical distribution of expected levels of thermal pollution.

between this experiment and the control experiment is also shown in Fig. 2, and the difference in rms global temperature is shown in Fig. 1. We note that this experiment shows the same results as the positive thermal energy and the random initial error experiments.

4. Conclusions

Our basic conclusion is that with the expected levels of man's thermal energy production, there is a relatively small modification of the model earth-atmosphere heat balance. The differences in numerical experiments with and without thermal energy input produce changes of the same order as the natural fluctuations of the model. These experiments have the serious shortcoming of assuming fixed ocean surface temperatures and thus should be repeated with a coupled atmosphere-ocean model.

We have not precluded by this study other possible mechanisms by which man may be changing the climate. For example, Rasool and Schneider (1971) have recently suggested that an increase in atmospheric aerosol content by a factor of 4 may lead to a 3.5C decrease in the surface temperature. They attribute this effect to increased backscattering of solar radiation caused by aerosols. Because the solar flux is such a large part of the surface energy budget, this sort of effect could easily mask the smaller effect of thermal energy.

Furthermore, we know from geological records that natural fluctuations in climate occur, causing temperatures over large areas of the globe to vary by several degrees. Before we can predict the small effect of man's activities on climate, we must be able to understand these natural fluctuations.

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