FURTHER STUDIES OF THE IMPACT OF WASTE HEAT RELEASE ON SIMULATED GLOBAL CLIMATE

Part II

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PREFACE

The IIASA Energy Program is studying global aspects of energy systems in terms of resources, demands, options, strategies, and constraints. One constraint on any energy system is represented by its impact on climate.

Part I by Williams et al., (1977) of this series of Research Memoranda on the impact of waste heat release on simulated global climate followed the lines of RM-76-79 by Murphy et al. (1976). They describe some results of three experiments with a numerical model of climate. These experiments were set up to investigate the possible impact of waste heat release from large-scale energy parks on the simulated atmospheric circulation. This part II describes a fourth experiment made with the same model, and compares the results with those of the first three experiments.

In addition, the analysis of all four energy parks experiments was extended by looking at three more climate variables and also by using some further methods.

With regard to the impact of energy systems on climate, there are of course still questions to be examined, and there will be more experiments and case studies to continue this work.

This research is part of the joint United Nations Environment Program (UNEP)/IIASA project on Energy and Climate and has been supported by the Meteorological Office, UK and the Kernforschungszentrum Karlsruhe GmbH, FRG.

SUMMARY

The general circulation model (GCM) of the Meteorological Office, UK (UKMO), has been used to investigate the impact of an input of waste heat (1.5 x 10^{14} W equally divided between two energy parks) into the atmosphere. This experiment is the fourth of a series of experiments made to investigate the behavior of the simulated circulation with different scenarios and energy releases. The results of this experiment have been compared with those of three earlier experiments described in Murphy et al. (1976) and Williams et al. (1977).

Although the total heat input was the same as in a previous experiment, the different locations of the heat islands caused a different response in the various climatic variables. It also can be said that EX04, in general, produced smaller changes than the previous experiments. They are, however, still significant.

Temperature and wind at σ level 0.5 have been considered for all experiments as this has not previously been done for any of the experiments.

Finally, a new attempt has been undertaken to assess the model variability by using 10-day means instead of 40-day means for calculating the standard deviation of the control cases. The signal-to-noise ratios have been recalculated, and a much smoother distribution has been obtained.

TABLES OF CONTENTS

LIST OF FIGURES

in EX01 to the standard deviation of that variable in the three control experiments (contour interval 4 units).

11b. The ratio of the differences in temperature at σ-level 0.5 in EX02 to the standard deviation of that variable in the three control experiments (contour interval 2 units).

11c. The ratio of the differences in temperature at σ-level 0.5 in EX03 to the standard deviation of that variable in the three control experiments (contour interval 2 units).

11d. The ratio of the differences in temperature at σ-level 0.5 in EX04 to the standard deviation of that variable in the three control experiments (contour interval 2 units).

12a. The ratio of the differences in the north-south component of the wind (in m/sec) at σ-level 0.5 in EX01 to the standard deviation of that variable in the three control experiments (contour interval 4 units).

12b. The ratio of the differences in the north-south component of the wind (in m/sec) at σ-level 0.5 in EX02 to the standard deviation of that variable in the three control experiments (contour interval 4 units).

12c. The ratio of the differences in the north-south component of the wind (in m/sec) at σ-level 0.5 in EX03 to the standard deviation of that variable in the three control experiments (contour interval 4 units).

12d. The ratio of the differences in the north-south component of the wind (in m/sec) at σ-level 0.5 in EX04 to the standard deviation of that variable in the three control experiments (contour interval 4 units).

13. The differences in surface pressure between EX01, EX03, EX04 and the average of the three control cases along the latitude line 49.5^{0}N.

14. The differences in surface pressure between EX01, EX04 and the average of the three control cases along the latitude line 37.5^{0}N.

15. Standard deviation of the 40-day mean surface pressure field computed from the three control cases (contour interval 4 units).

16. Estimate of the standard deviation of 40-day mean sea-level pressure computed from the data of Schumann and Van Rooy (1952) (contour interval 2 units).
17. Standard deviation of the 10-day mean surface pressure field computed from the three control cases (contour interval 2 units).
18. The ratio of the differences in surface pressure in EX01 to the 10-day standard deviation of that variable in the three control experiments (contour interval 2 units).
19. The ratio of the differences in temperature in the lowest layer of the model in EX01 to the 10-day standard deviation of that variable in the three control experiments (contour interval 2 units).
20. The ratio of the differences in temperature in the lowest layer of the model in EX02 to the 10-day standard deviation of that variable in the three control experiments (contour interval 2 units).
21. The ratio of the differences in surface pressure in EX04 to the 10-day standard deviation of that variable in the three control experiments (contour interval 2 units).
22. The ratio of the differences in temperature at σ-level 0.5 in EX04 to the 10-day standard deviation of that variable in the three control experiments (contour interval 2 units).

Further Studies of the Impact of Waste Heat Release on Simulated Global Climate

Part II

1. INTRODUCTION

This paper is a further installment in a series of documents describing the IIASA Energy Program study at the possible impacts of energy systems on climate. The study involves a comparison of the various energy options (fossil fuel, nuclear, and solar) in terms of their different influences on climate in the medium- and long-term future.

The first step of this research has been to explore the possible climatic effects resulting from the existence of ocean energy parks, from which large amounts of waste heat from power stations would be released into the atmosphere and ocean. An agreement was reached between the International Institute for Applied Systems Analysis (IIASA) and the Meteorological Office, UK (herein referred to as UKMO), that the model of the atmospheric general circulation developed at the UKMO would be used in these studies.

Two IIASA Research Memoranda (RM-76-79, Murphy et al., 1976; and RM-77-15, Williams et al., 1977) described the setting up and running of the first three experiments and some of the results. Basically, the energy was released into the atmosphere from one or two small energy parks and the experiments were conducted to study the model's behavior with different park locations.

The use of numerical models to simulate climate and investigate its sensitivity to different perturbations has been described, for example, by Smagorinsky (1974), Schneider and Dickinson (1974) and Williams (1977). Basically, the atmospheric general circulation model solves a set of equations governing the thermodynamical and dynamical state of the atmosphere (together with other equations of state and conservation laws) on a set of grid points which, in the case of the model that we are using, covers the northern hemisphere.

It is found that when the equations are solved with boundary conditions representing, for example, January of the present day, the model quite realistically reproduces the basic features of the earth's climate. It is recognized that atmospheric GCMs have shortcomings. In particular, the absence of a joint atmosphere-ocean system, poor treatment of clouds and hydrological processes and of many sub-grid scale processes have been noted. Despite these shortcomings, models of the atmospheric general circulation are used to study the impacts of factors such as sea-surface temperature anomalies, increased atmospheric carbon dioxide, and waste heat upon the simulated climate, since the models still represent the best tool available for studying the climate system and mechanisms. In particular, the sensitivity experiments may indicate the changes to be expected even if the basic state is not simulated perfectly.

In this paper the results of a fourth energy parks experiment are described and compared with those of the earlier experiments. In addition, the analysis of all four experiments will be continued by looking at wind and temperature fields at σ-level 0.5. Finally, the model variability is discussed and a new estimate for the significance of the results is given.

2. EXPERIMENT 04

2.1 The Scenario for Experiment 04

The IIASA-UKMO experiments (Murphy et al., 1976; Williams et al., 1977) were designed to study the impact of ocean energy parks on simulated climate. The concept of large-scale nuclear energy parks determined the scenarios selected for the experiments.

If each park is designated with a letter, then in the four energy parks experiments three parks with the following locations have been used:

A. 49.5^0N, 12.0 - 16.5^0W; 46.5^0N, 14.0 - 18.5^0W
B. 10.5^0N, 21.0 - 24.0^0W; 7.5^0N, 20.5 - 23.5^0W
C. 37.5^0N, 146.0 - 150.0^0E; 34.5^0N, 145.5 - 148.5^0E

Figure 1 shows the locations. In EX01 the impact of a combination of parks A and C was investigated; i.e. one park in the midlatitude Atlantic and one in the midlatitude Pacific.

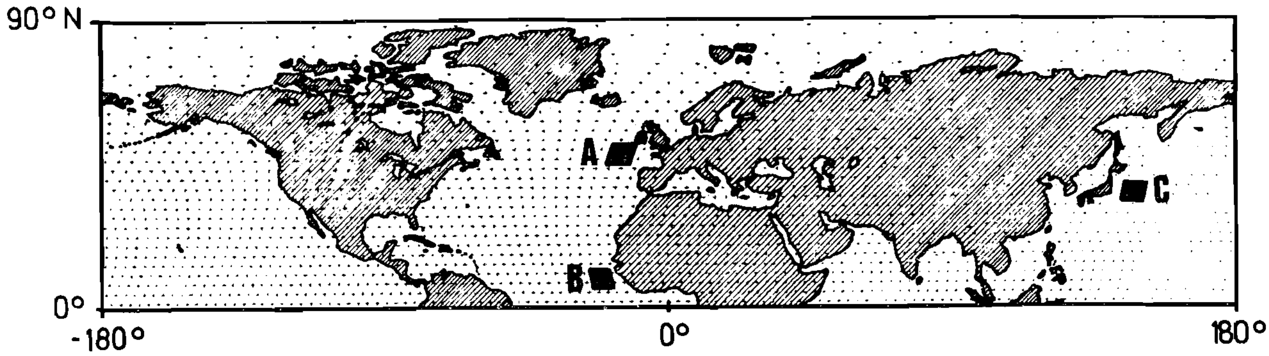

Figure 1. Locations of the three energy parks.

At each park the heat input was $1.5x10^{14}$ W, which gave a total heat input, therefore, of $3.0x10^{14}$ W.

In EX02 the impact of a combination of parks B and C was investigated; i.e. the same park in the Pacific Ocean as in EX01 but with a tropical Atlantic park. At each park the heat input was again $1.5x10^{14}$ W, giving the same total heat input as in EX01.

In EX04 the impact of parks A and C was again studied, i.e. the parks were in the same location as in EX01. The heat input at each park was $0.75x10^{14}$ W, half as much as in EX01.

As pointed out by Murphy et al. (1976), the energy parks cannot be simulated in a completely realistic way because the real area of such a park is too small to be properly represented within the grid structure of the model, and because a realistic scenario would involve the spread of heat by ocean currents and, therefore, would require a linked atmosphere-ocean model. We therefore made the area of each park equal to four grid boxes in the model.

In experiments EX01 to EX04 the waste heat was inserted directly into the atmosphere in sensible form, by adding 275 Wm^{-2}

(137,5 W m^{-2} in EX04) to the sensible heat exchange routine of the model at the four grid points within each park.

2.2 Results of Experiment 04

In addition to the energy parks experiments, three control cases, run with the same model, are available. These control cases simulate January climate without any imposed perturbation and differ from each other because of the addition of random differences in the initial conditions.

Figure 2 shows the differences in 40-day mean (days 41 to 80) surface pressure between EX04 and the average of the three control cases. Over both of the energy parks there was a small surface pressure decrease (4mb over Atlantic park and 3mb over Pacific park). In EX01 the parks experienced opposite pressure changes, with the Atlantic park having a 12mb pressure increase and the Pacific park a 6 to 8mb decrease. The response over the parks in the surface pressure field is therefore of different magnitude and, in one case, sign when the energy input is halved.

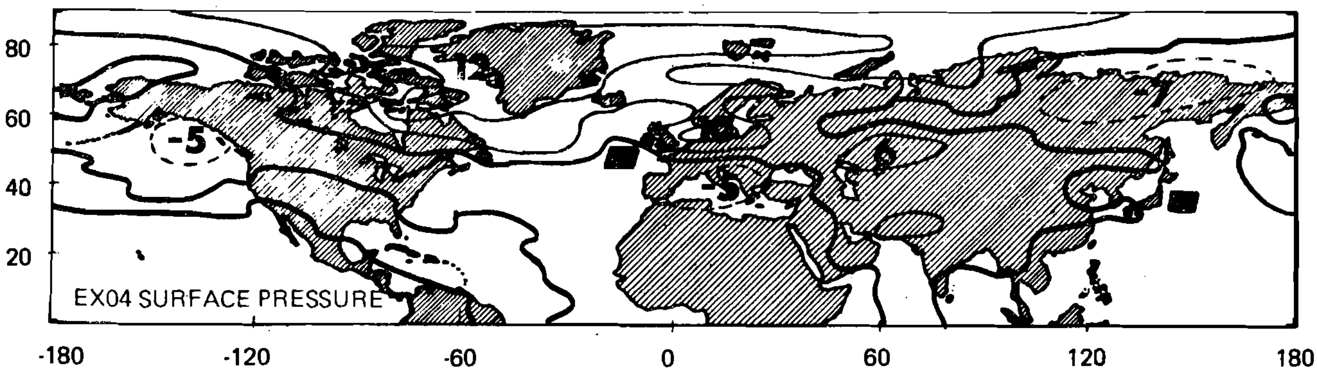

Figure 2. The differences in 40-day surface pressure between EX04 and the average of the three control experiments (contours at every 4 MB).

Elsewhere over the hemisphere the surface pressure changes are smaller than those found in EX01. The largest changes are the pressure increases over Europe (+10mb) and the eastern Canadian Arctic (+13mb). Particularly noticeable is the absence of a large surface pressure response over Siberia (only -7mb in EX04) compared with large responses in previous experiments. As in the earlier experiments the pressure changes are confined to middle and high latitudes.

Figure 3 illustrates the differences in the 40-day mean surface pressure distributions between EX01 and EX04. The contours on this map closely resemble those of the surface pressure differences between EX01 and the control cases (see Murphy et al., 1976, Figure 8a) because the changes in EX01 were large compared with those in EX04. It may be observed from Figure 3 that the response over the European, Siberian and Canadian Arctic areas was different in the two experiments.

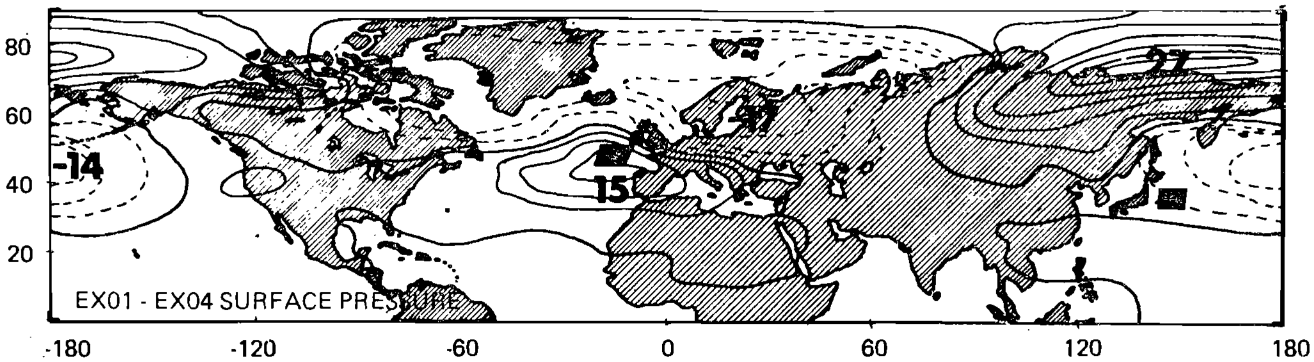

Figure 3. The differences in 40-day surface pressure between EX01 and EX04 (contours at every 4 MB).

Comparison of the surface pressure changes in EX04 with those in EX03 (not illustrated here) (see Williams et al., 1977, Figure 2) shows that there are different responses depending on whether the heat ($1.5x10^{14}$ W) is put into the atmosphere in one (EX03) or two (EX04) energy parks. The surface pressure change in Europe was negative (-11mb) and very large and positive (+29mb) over Siberia in EX03. In general the magnitude of the changes in EX03 were larger than those in EX04.

The ratio of the surface pressure differences between EX04 and the three controls to the standard deviation of the surface pressure in the three controls is illustrated in Figure 4. As explained elsewhere (Murphy et al., 1976; Williams et al., 1977),

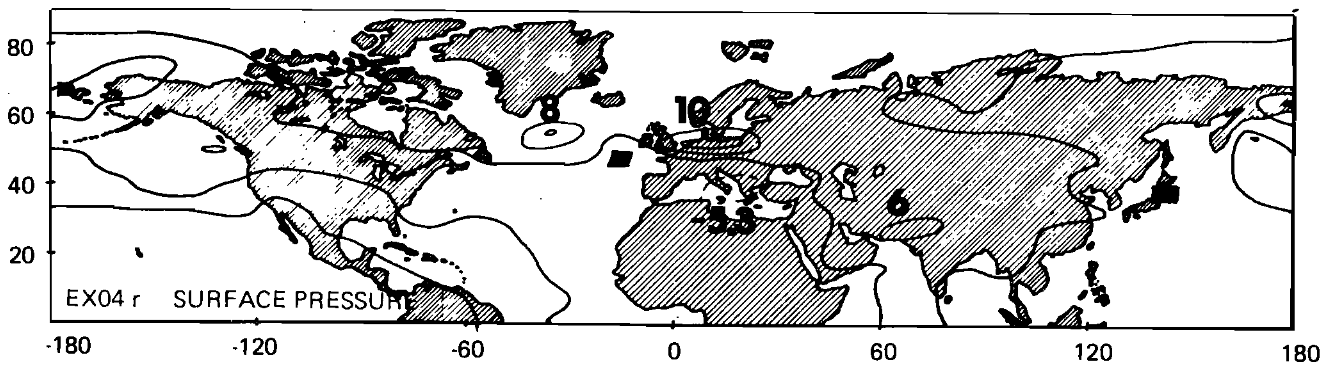

Figure 4. The ratio of the differences in surface pressure in EX04 to the standard deviation of that variable in the three control experiments (contour interval 4 units).

the values of this ratio greater than about 5 indicate a 95 per cent probability that the null hypothesis that no significant change occured in the model's January surface pressure field due to the energy parks can be rejected. As far as the surface pressure field is concerned, the values of the ratio suggest that significant changes occured over Europe, the Mediterranean, the Atlantic south of Greenland, possibly off the northwest coast of North America, and northeast of India. In contrast to the values of the ratio for EX01 (see Murphy et al., 1976, Figure 11a), no large values of the ratio are found over the energy parks themselves in EX04, but quite widespread large values of the ratio are found elsewhere in the hemisphere.

The differences in temperature at $\sigma = 0.9$ between EX04 and the average of the controls are shown in Figure 5. As in the earlier experiments the temperature increased over the energy parks, but in EX04 this increase was less than 2^0C, compared with increases of 5^0C in EX01 and EX02 and 3^0C in EX03. Immediately on the downstream side of the Atlantic park in EX04 is an area of temperature decrease, but elsewhere over Europe and Asia the temperature changes are small. This again contrasts with the differences found in EX01 (Murphy et al., 1976, Figure 9a) where large changes occured over western Siberia and the

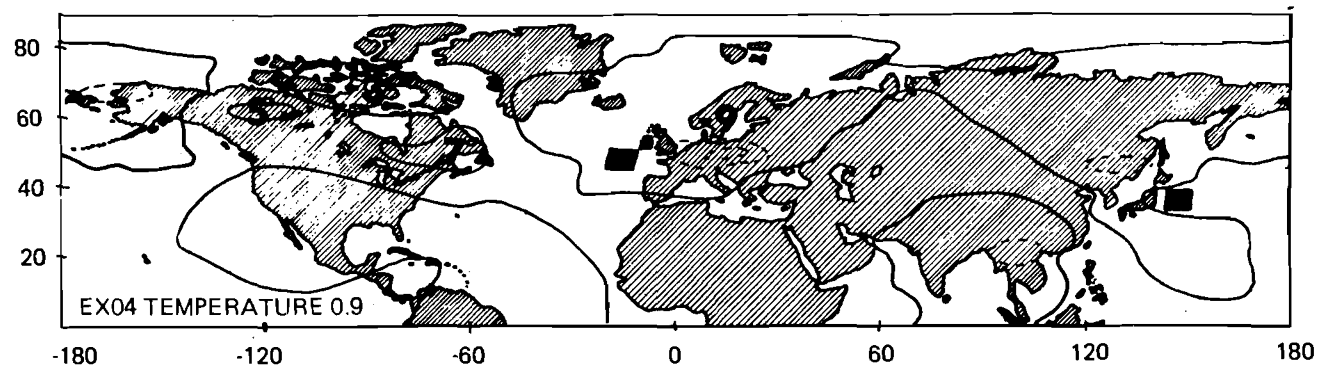

Figure 5. The differences in 40-day mean temperature (^{0}C) in the lowest layer of the model between EX04 and the average of the three control experiments (contours at every 4^{0}C).

USSR. The only other large temperature changes in EX04 are over Indonesia and Labrador. The increase in temperature over Labrador can be related to the increased flow of air from the Atlantic as shown in the surface pressure changes, while the decrease in temperature over northern Europe can be related to the increased easterly flow off the continent shown in the surface pressure changes. Since no large surface pressure changes occurred over Siberia as they did in EX01, one would not expect to find large temperature changes there.

The differences between EX01 and EX04 for the temperature at $\sigma = 0.9$ are shown in Figure 6. There are three large areas over which the temperature differences between the experiments are largely different: Eurasia, Kamchatka and Alaska, and North America. That is, in general the temperature changes over the ocean areas were similar in the two experiments but differed over continental areas. It must be emphasized that EX01 and EX04 did not differ in the same direction over all continental areas: in EX01 Eurasia was warmer (by up to 11^{0}C) than EX04, while North America was cooler (by up to 14^{0}C). This illustrates the non-linearity of the model response to the heat input. When the heat

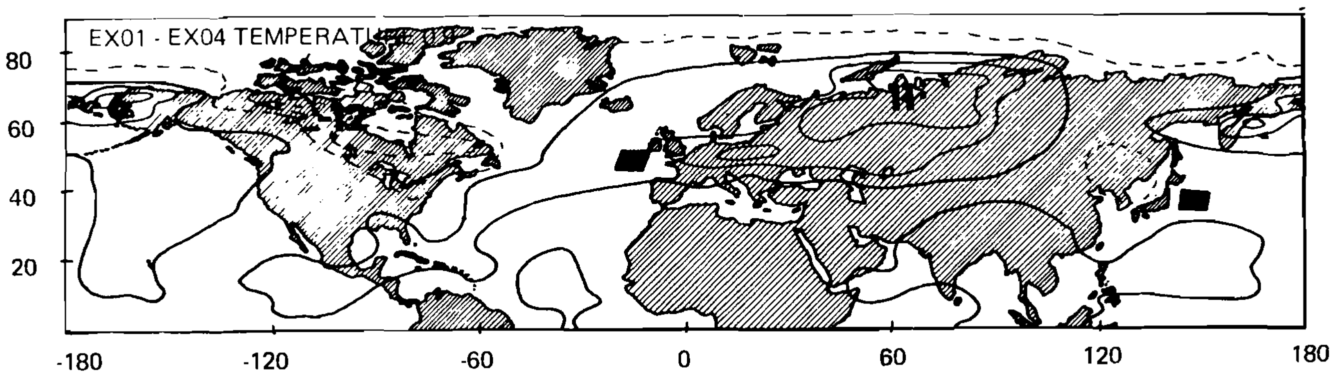

Figure 6. The differences in 40-day mean temperature in the lowest layer of the model between EX01 and EX04 (contours at every 4 ^{0}C).

input is halved the temperatures in the lower atmosphere of the model do not respond in the same way as they did in EX01.

Likewise, differences between EX03 and EX04 for the temperature at σ = 0.9 show that the location of the heat input is of importance to the response of the variable. In EX03 the temperature decrease on the downstream side of the Atlantic energy park was further north than that in EX04; over the rest of Asia the temperature changes were a little larger and distributed quite differently in EX03 than EX04. Over North America the patterns of temperature change in EX03 and EX04 have some similarities.

The values of the ratio for T at σ = 0.9 in EX04 are shown in Figure 7. There are several areas of apparently significant values of the ratio, in particular over Europe, the Arabian Peninsula, southeast Asia, the Pacific energy park, and Labrador. In several cases the areas of significant temperature change are related to the areas of significant surface pressure change, emphasizing that the temperature response is primarily due to advection changes caused by changes in the surface pressure field. Comparing Figure 7 with the equivalent figure for EX01 (see Murphy et al., 1976, Figure 13a), it is noticeable that, unlike

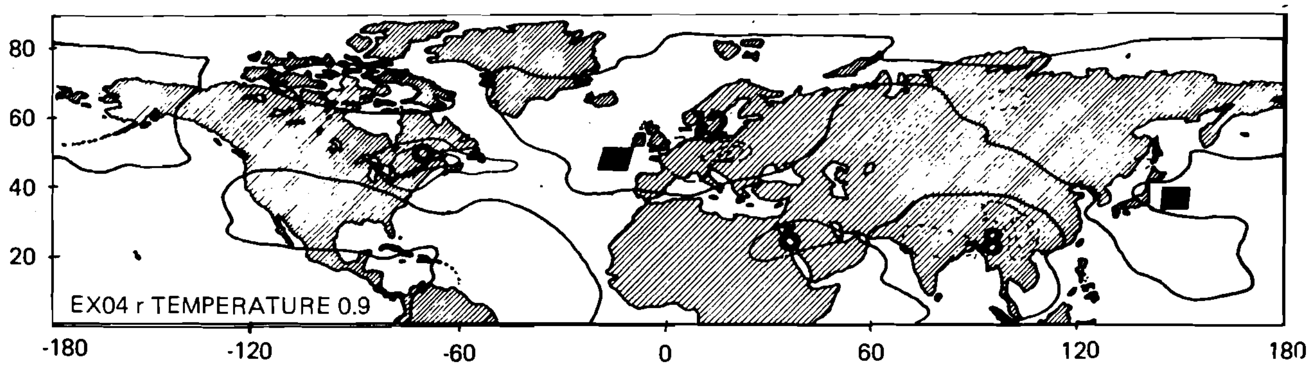

Figure 7. The ratio of the differences in temperature in the lowest layer of the model in EX04 to the standard deviation of that variable in the three control experiments (contour interval 4 units).

the EX01, EX04 did not produce large values of the ratio in the vicinity of the parks, nor is there a large value over the Siberian area in EX04. Particularly noticeable are the large values of the ratio over the Arabian Peninsula and southeast Asia in EX04, since these areas do not have large values of the ratio in any of the first three energy parks experiments. All experiments, however, have a similar pattern of the ratio over the Labrador area, and this suggests a low value of the standard deviation of the three control cases in this area, a point which will be discussed further later.

The differences in precipitation between EX04 and the average of the three control experiments are shown in Figure 8. As in earlier energy parks experiments the largest changes are in the tropics, and there are no large precipitation changes in the middle and high latitudes in EX04. Over neither of the energy parks is there a large change in precipitation in EX04, a feature which was also noted in EX01.

The significance ratios for the precipitation differences in EX04 are given in Figure 9. In this case, significant values are found over and upstream of the Atlantic energy park, and not in the vicinity of the Pacific park--this was also found in EX01

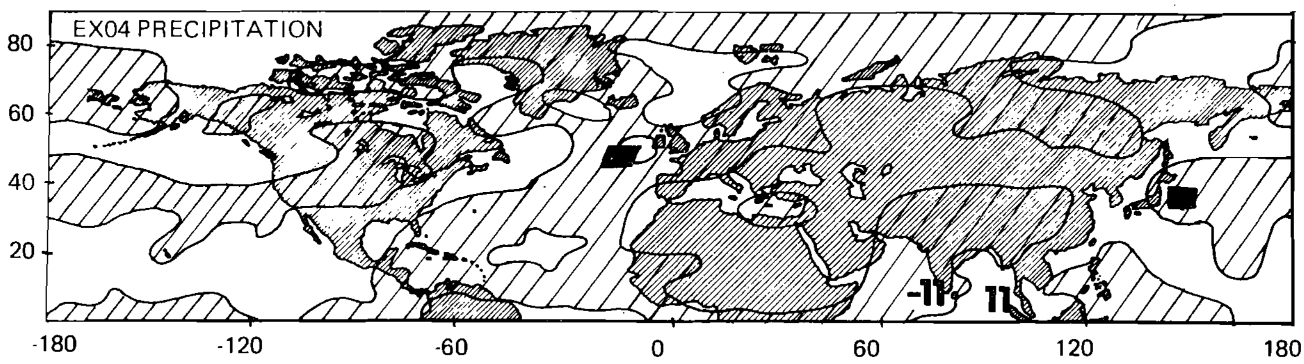

Figure 8. The differences in 40-day mean total precipitation (in mm/day) between EX04 and the average of the three control experiments.

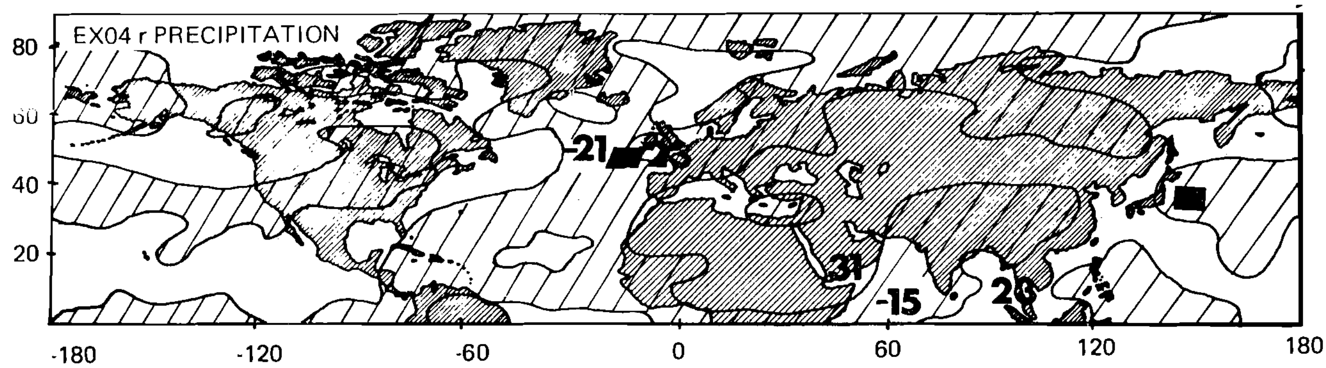

Figure 9. The ratio of the differences in total precipitation in EX04 to the standard deviation of that variable in the three control experiments.

(Murphy et al., 1976, Figure 14a). Over the tropical areas the large values of the ratio are distributed in somewhat random fashion. As pointed out by Murphy et al. (1976), these large values are probably not significant because rainfall in the tropics arises primarily as a result of local instabilities and the assumption of normality, which is required for the application of significance tests to the t-statistic, does not hold. Values which are apparently significant in the precipitation differences can occur by chance.

Nevertheless, the response of the precipitation in the areas of the energy parks is very similar in EX01 and EX04, and in the vicinity of the mid-latitude Atlantic park it was again similar in EX03. It seems, therefore, that the decrease of precipitation in a band on the upstream side of the midlatitude Atlantic energy park and the increase immediately downstream are consistent responses in the energy parks experiments. Comparing the changes in precipitation in the vicinity of Atlantic energy parks with the pressure changes, one sees that the precipitation decrease on the upstream side of the park is associated with a pressure increase, and the precipitation increase over and immediately on the downstream side of the park is associated with a pressure decrease. In other words, there is evidence in both the pressure and precipitation changes that the midlatitude Atlantic energy park in EX01, EX03 and EX04 has caused a change in the depression track in the east Atlantic as noted by Gilchrist (1975) for EX01. This change has been induced both by a heat input of 1.5×10^{14} W (EX01 and EX03) and 0.75×10^{14} W (EX04). When the Atlantic park was situated in the tropical latitudes, the major effect on the precipitation was to drastically increase it immediately over the park. In neither EX01, EX02, nor EX04 has the Pacific energy park had a significant effect on precipitation.

3. WIND AND TEMPERATURE AT $\sigma = 0.5$ IN ALL EXPERIMENTS

So far, we have concentrated on changes in surface variables between the control cases and each energy parks experiments. In this section changes at $\sigma = 0.5$ (about 500mb), i.e. in the mid-troposphere, will be discussed.

Figures 10a to d show the differences in temperature at $\sigma = 0.5$ between the energy parks experiments and the average of the control cases. For EX01 (Figure 10a) we see that the changes are smaller than those at the surface, but still of considerable magnitude. Over the Atlantic park and upstream there is a temperature increase of up to 4^0C, and there is also an increase over the western USSR. In both of the latter areas the temperature increased at the surface (see Figure 9a in Murphy et al., 1976). Over the Pacific energy park and both upstream and downstream the temperature decreased at $\sigma = 0.5$; at the surface there was a small temperature increase over the park, and decreases around it.

In EX03 (Figure 10b) the changes in temperature at $\sigma = 0.5$ are not as large as in EX01. In the eastern Pacific and over western Europe the temperature has increased by 3 to 4^0C but elsewhere changes are small, and it is particularly noticeable that there are no large changes in the vicinity of the energy parks. In EX03 (Figure 10c) the temperature changes at $\sigma = 0.5$ are ± 3 to 5^0C and show a strong wave 3 pattern in middle latitudes. The areas of greatest temperature change at $\sigma = 0.5$ correspond to the areas of greatest temperature change at $\sigma = 0.9$, i.e. the effects of the energy input are not only found in the surface layer of the atmosphere but have been carried at least as far as the mid-troposphere.

In EX04 (Figure 10d) the changes in temperature at $\sigma = 0.5$ are very small--in only two areas, east of the Caspian Sea and the eastern Canadian Arctic are the changes greater than 2^0C. In the case of EX04 therefore, the temperature changes in the surface layer are not clearly identifiable at $\sigma = 0.5$. For example, at $\sigma = 0.9$ the largest temperature (-9^0C) was found over western and central Europe, but no large temperature

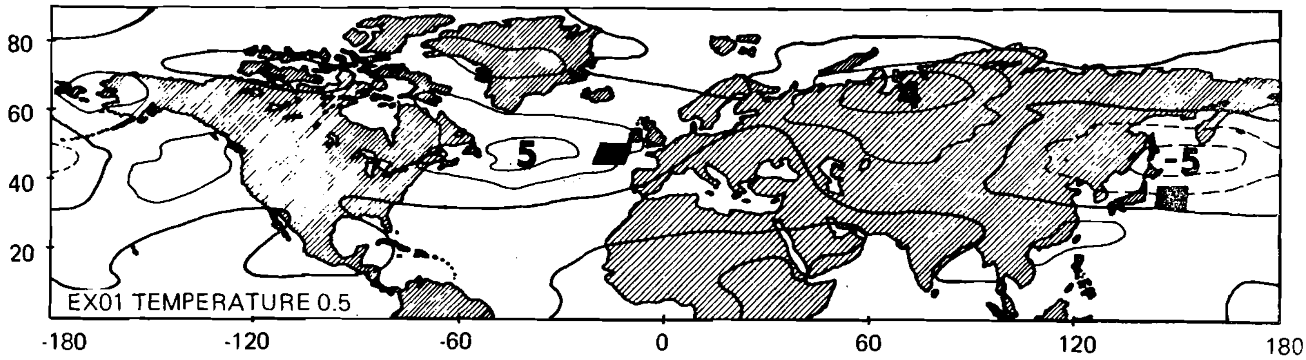

Figure 10a. The differences in 40-day mean temperature at σ-level 0.5 between EX01 and the average of the three control experiments (contours at every 2^0C).

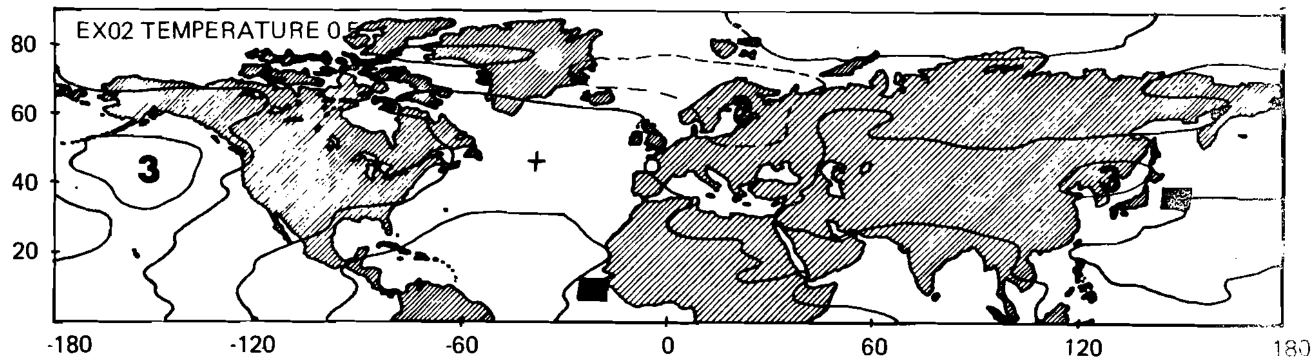

Figure 10b. The differences in 40-day mean temperature at σ-level 0.5 between EX02 and the average of the three control experiments (contours at every 2^0C).

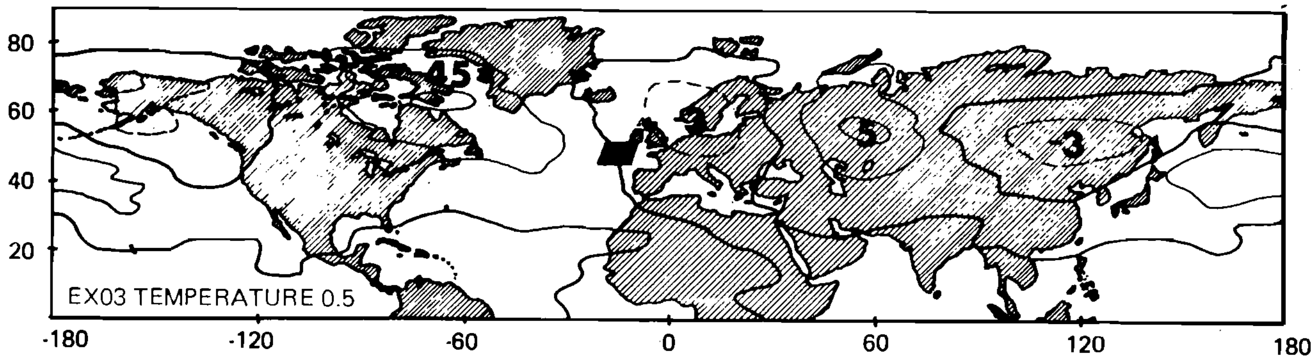

Figure 10c. The differences in 40-day mean temperature at σ-level 0.5 between EX03 and the average of the three control experiments (contours at every 2^0C).

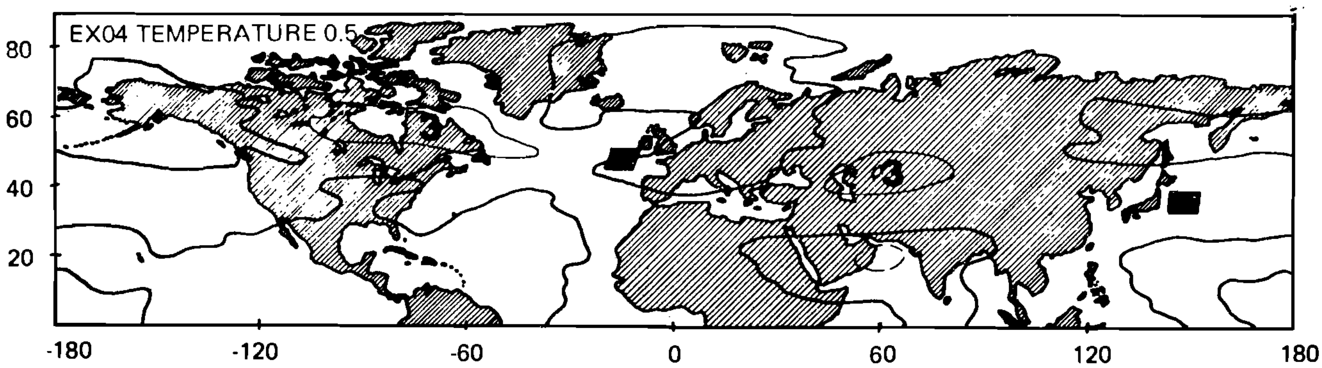

Figure 10d. The differences in 40-day mean temperature at σ-level 0.5 between EX04 and the average of the three control experiments (contours at every 2^0C).

change is seen in this area at $\sigma = 0.5$

The significance ratios computed for the temperature changes at $\sigma = 0.5$ are shown in Figures 11a to d. Although the absolute values of the temperature changes are smaller at $\sigma = 0.5$ than at $\sigma = 0.9$, the variability at this level is also smaller, so that values of the ratio (difference between energy park experiment and average of controls divided by standard deviation of controls) can still be found to be greater than 5.0. Thus, in EX01 (Figure 11a) we see that there are several areas in the mid-latitudes where the value of the ratio is significant. Over both energy parks the values of the ratio are much greater than 5.0. There is quite a lot of similarity between the distribution of the ratio at $\sigma = 0.5$ and that at $\sigma = 0.9$ for EX01.

In EX02 (Figure 11b) there are really only two areas in which the temperature change at $\sigma = 0.5$ can be considered significant (in the Gulf of Alaska and over Scandinavia). At $\sigma = 0.5$ no large values are found over the parks, showing that the immediate temperature effect of the energy parks in EX02 was concentrated at the surface and was not carried up into the atmosphere. The same effect is noted for the energy park in EX03 (see Figure 11c, and Williams et al., 1977, Figure 5). In EX04 (Figure 11d) there is only one area over which the value of the ratio for temperature at $\sigma = 0.5$ is greater than 5.0 and this is centered over Labrador, in almost the same area as the significant values of the ratio in EX03.

It is very interesting to note that the values of the ratio in the area of the park are only significant (or, for that matter, of any magnitude at all) at $\sigma = 0.5$ in EX01; in the other three experiments the influence of the parks on the temperatures directly above the park did not continue into the mid-troposphere.

Changes in the value of the u-(west-east) component of the wind at $\sigma = 0.5$ give some information regarding changes in, for example, the jet stream circulation. Both observational and theoretical work (reviewed, for example by Palmen and Newton, 1969) show that the flow at the 500mb level is influenced by the thermal and orographic characteristics of the earth's surface;

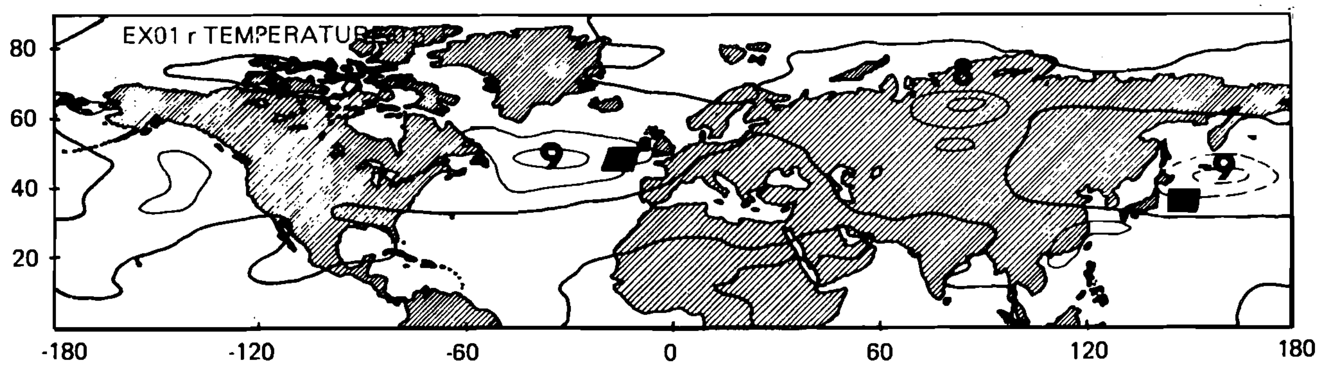

Figure 11a. The ratio of the differences in temperature at σ-level 0.5 in EX01 to the standard deviation of that variable in the three control experiments (contour interval 4 units).

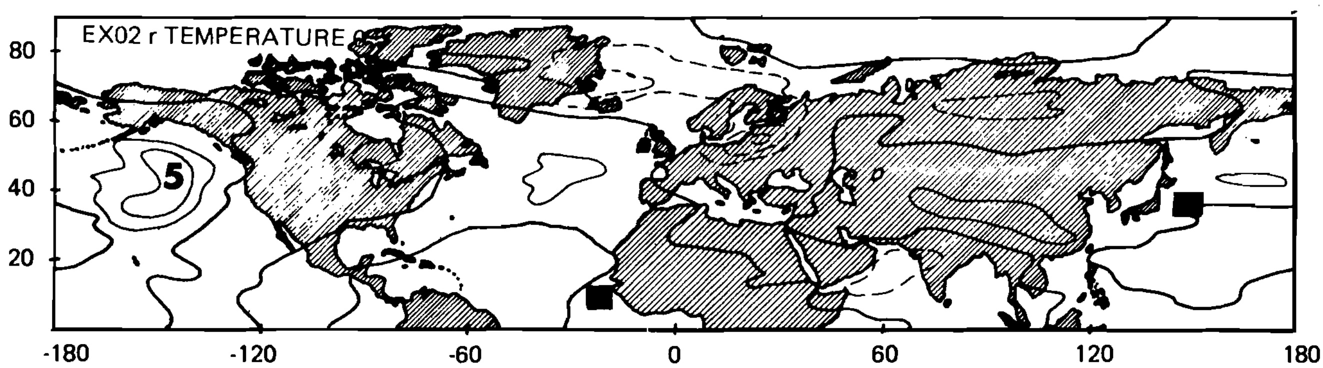

Figure 11b. The ratio of the differences in temperature at σ-level 0.5 in EX02 to the standard deviation of that variable in the three control experiments (contour interval 2 units).

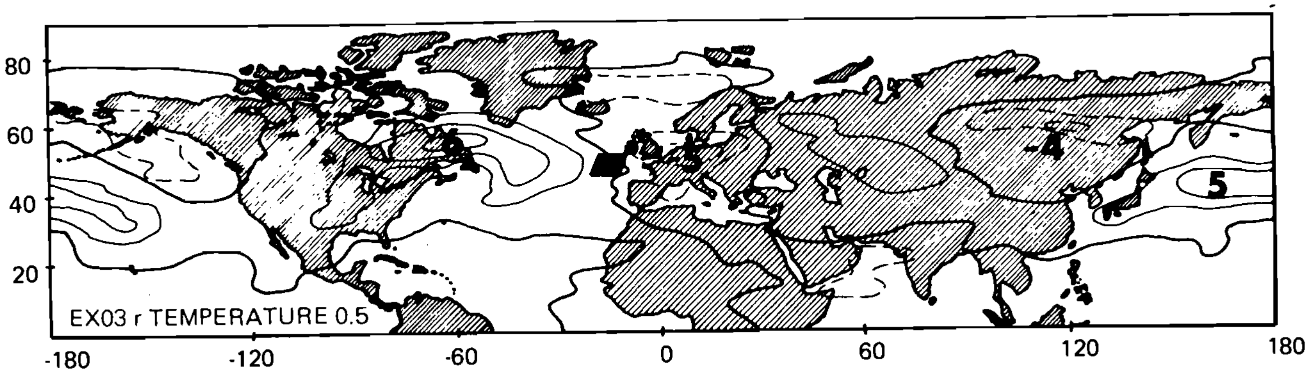

Figure 11c. The ratio of the differences in temperature at σ-level 0.5 in EX03 to the standard deviation of that variable in the three control experiments (contour interval 2 units).

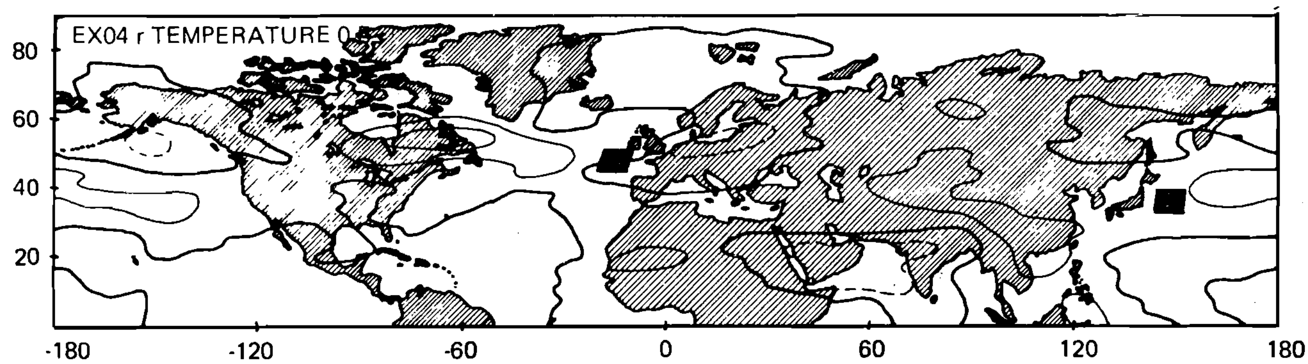

Figure 11d. The ratio of the differences in temperature at σ-level 0.5 in EX04 to the standard deviation of that variable in the three control experiments (contour interval 2 units).

so it is very possible that the energy input in EX01 to EX04 will also have had an influence on the circulation at $\sigma = 0.5$.

In EX01 there are large changes in the u-component of the wind at $\sigma = 0.5$. South of the Atlantic energy park there was a decreased westerly (or increased easterly) flow, while north of the park there was an increased westerly (decreased easterly) flow. Over the Atlantic park therefore, at $\sigma = 0.5$, the flow was more anticyclonic in EX01 than in the control cases; an increase in surface pressure was alos noted in the same region. Over the Pacific park and upstream and downstream in EX01, the flow was more westerly (less easterly) at $\sigma = 0.5$. To the north of the Pacific park there was a decreased wasterly flow, leading to an increased cyclonic circulation at $\sigma = 0.5$ over the Pacific Ocean, corresponding to the surface pressure decrease.

Magnitudes of changes in the u-component of the wind at $\sigma = 0.5$ in EX02 are not so large as in EX01. Over the Pacific energy park the change is much smaller than in EX01, and over the Atlantic park--which in this case is in the tropical Atlantic--the area of large change is very small. Over the tropical Atlantic park the wind at $\sigma = 0.5$ is more easterly (less westerly) in EX02 than in the three control cases, while to the south of the park the flow is more westerly; this means that there was an increased cyclonic flow over the tropical Atlantic park in contrast to the increased anticyclonic flow over the mid-latitude Atlantic park in EX01.

In EX03 the changes in the u-component of the wind at $\sigma = 0.5$ do not show the large changes in the vicinity of the mid-latitude energy park as found in EX01. South of the park there is a decreased westerly flow in EX03, but the increase north of the park in EX01 is not seen in EX03.

The change in the u-component of the wind is also different in EX04 from EX01. In EX04 the wind upstream and on the downstream side of the Atlantic park had a decreased westerly component, and in the vicinity of the Pacific park there is also a decreased westerly component, but the decrease is not as large as in EX01. The large changes in circulation over the Pacific and Atlantic oceans at $\sigma = 0.5$ in EX01 are not seen in EX04.

Significance ratios for the u-component of the wind at $\sigma = 0.5$ show that for EX01 the large changes in the Pacific Ocean, the Atlantic, and the Sahara can be attributed to the influence of the energy parks and not to model variability. Of interest are the large areas of significant values of the ratio in the eastern Pacific. In EX02 there are no large values of the ratio in the vicinity of the energy parks, again there is a large area of significant values in the eastern Pacific; scattered smaller areas of signifcant values occur.

In both EX03 and EX04 the areas over which the values of the significance ratio are greater than 5.0 are likewise scattered and not large; the total area of significant change is not as great as in EX01.

Figures 12a to d show the values of the significance ratio for the v-(north-south) component of the wind at $\sigma = 0.5$ for each energy park experiment. It is seen that large values of the ratio occur, over substantial areas. In EX01 there is a significantly increased southward (decreased northward) flow over the Atlantic energy park, with a significantly decreased southward (increased northward) flow to the west of the park, completing the increased anticyclonic circulation in the Atlantic area that was noted in the discussion of the u-component of the wind. In each experiment with an energy park in the midlatitude Atlantic (EX01, EX03, EX04) the flow over the Atlantic energy park became increasingly northerly (decreasing southerly). The increasing southerly flow to the west of the park is significant in EX01 and does not occur in EX03 and EX04. Over the Pacific energy park, on the other hand, the change in the v-component of the wind at $\sigma = 0.5$ is not similar in each experiment. In non of the experiments (EX01, EX02, EX04) is there a significant value of the ratio directly over the park, and in areas surrounding the park the significant values are in different places in each experiment. The similarity of the values of the ratios in EX01 EX02, and EX03 over the eastern Pacific Ocean suggests that the variance in the three control cases is small in this area--and

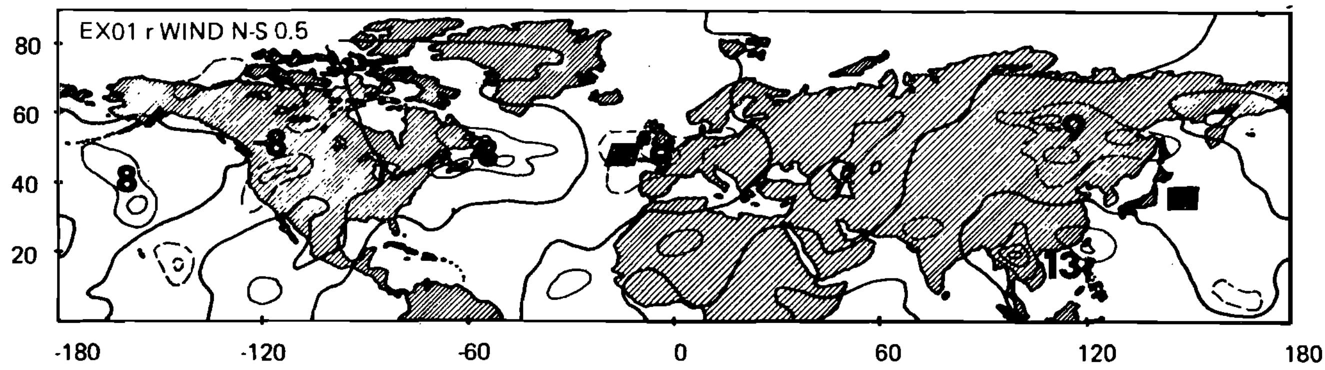

Figure 12a. The ratio of the differences in the north-south component of the wind (in m/sec) at σ-level 0.5 in EX01 to the standard deviation of that variable in the three control experiments (contour interval 4 units).

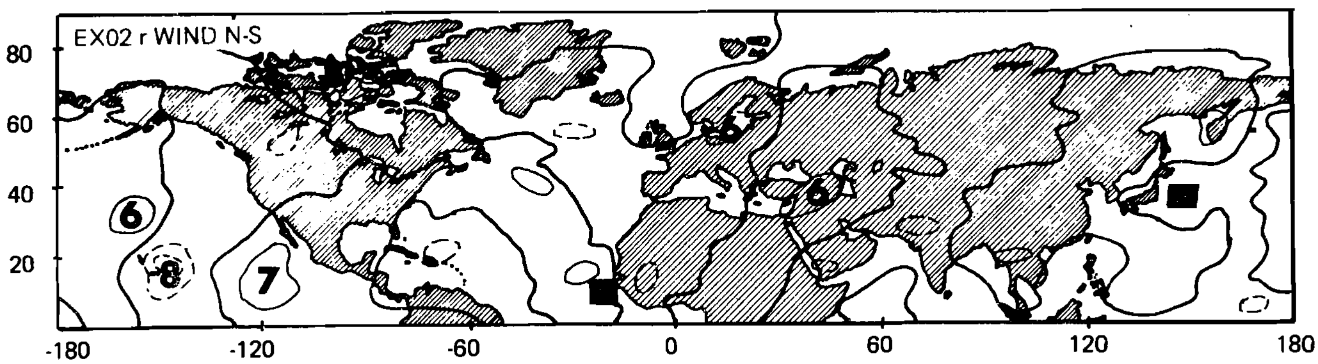

Figure 12b. The ratio of the differences in the north-south component of the wind (in m/sec) at σ-level 0.5 in EX02 to the standard deviation of that variable in the three control experiments (contour interval 4 units).

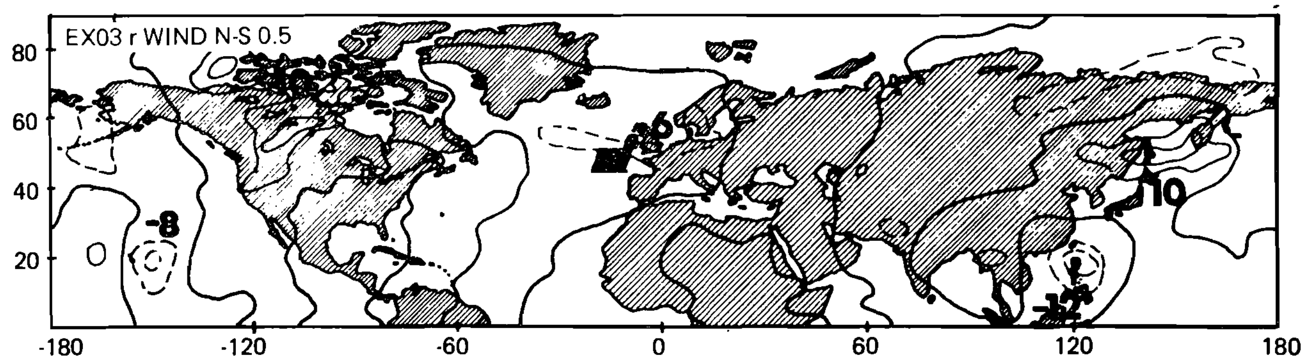

Figure 12c. The ratio of the differences in the north-south component of the wind (in m/sec) at σ-level 0.5 in EX03 to the standard deviation of that variable in the three control experiments (contour interval 4 units).

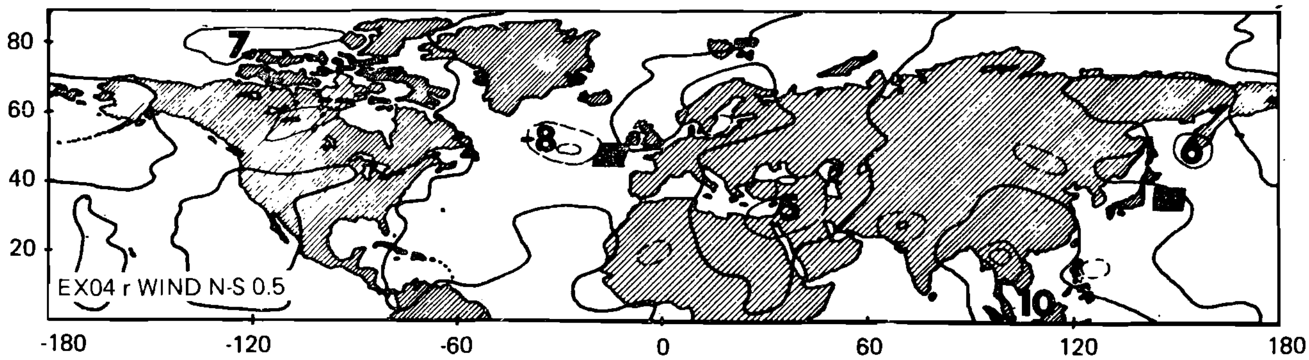

Figure 12d. The ratio of the differences in the north-south component of the wind (in m/sec) at σ-level 0.5 in EX04 to the standard deviation of that variable in the three control experiments (contour interval 4 units).

it is possible that the differences would not be significant if a larger sample of control cases were available.

4. SURFACE PRESSURE DIFFERENCES ALONG LATITUDE LINES THROUGH ENERGY PARKS

The difference in surface pressure between the control cases and EX01, EX03, and EX04 along the latitude line 49.5°N (which passes through the Atlantic energy park) are plotted in Figure 13. In EX01 there is a clear rise of pressure to the west and over the park, with a decrease east of the park. This pattern is repeated in EX03, emphasizing the point made by Williams et al. (1977; page 5 of that report) that the pattern of change in

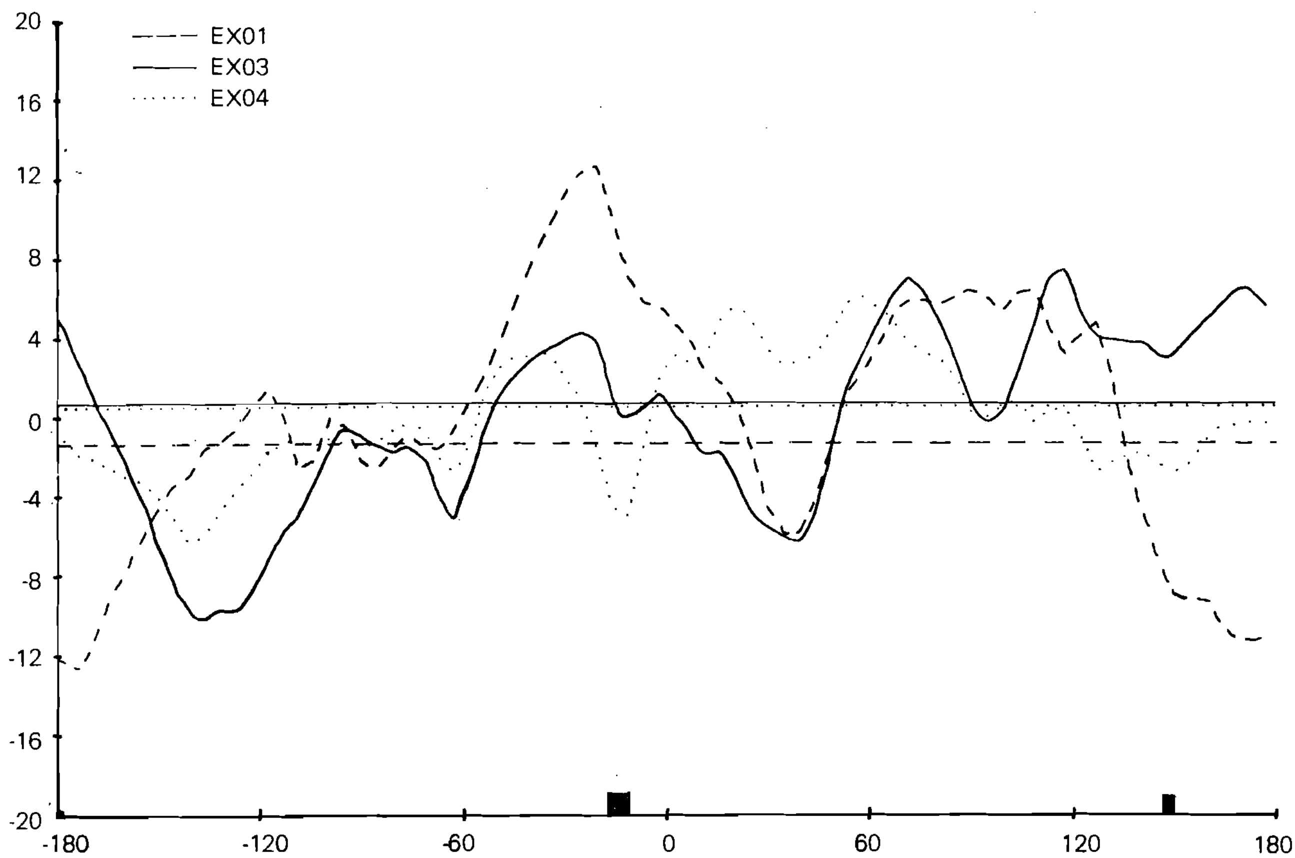

Figure 13. The differences in surface pressure between EX01, EXO3, EX04 and the average of the three control cases along the latitude line 49.5°N.

EX01 and EX03 in the vicinity of the Atlantic park is similar. In EX04 there is some similarity in the response over the Atlantic, although the pressure increase to the upstream side of the park is not as large or coherent as in EX01 and EX03 (and occurs further west), and the pressure decrease downstream is smaller and displaced towards the park. The similarity of the pressure changes in EX01 and EX03 immediately on the donwstream side of the parks is striking. Over the Pacific the large decrease of pressure noted in EX01 is not seen in the other two experiments.

At 37.5^{0}N (Figure 14), which passes through the Pacific energy park, we can compare the pressure differences in EX01 and

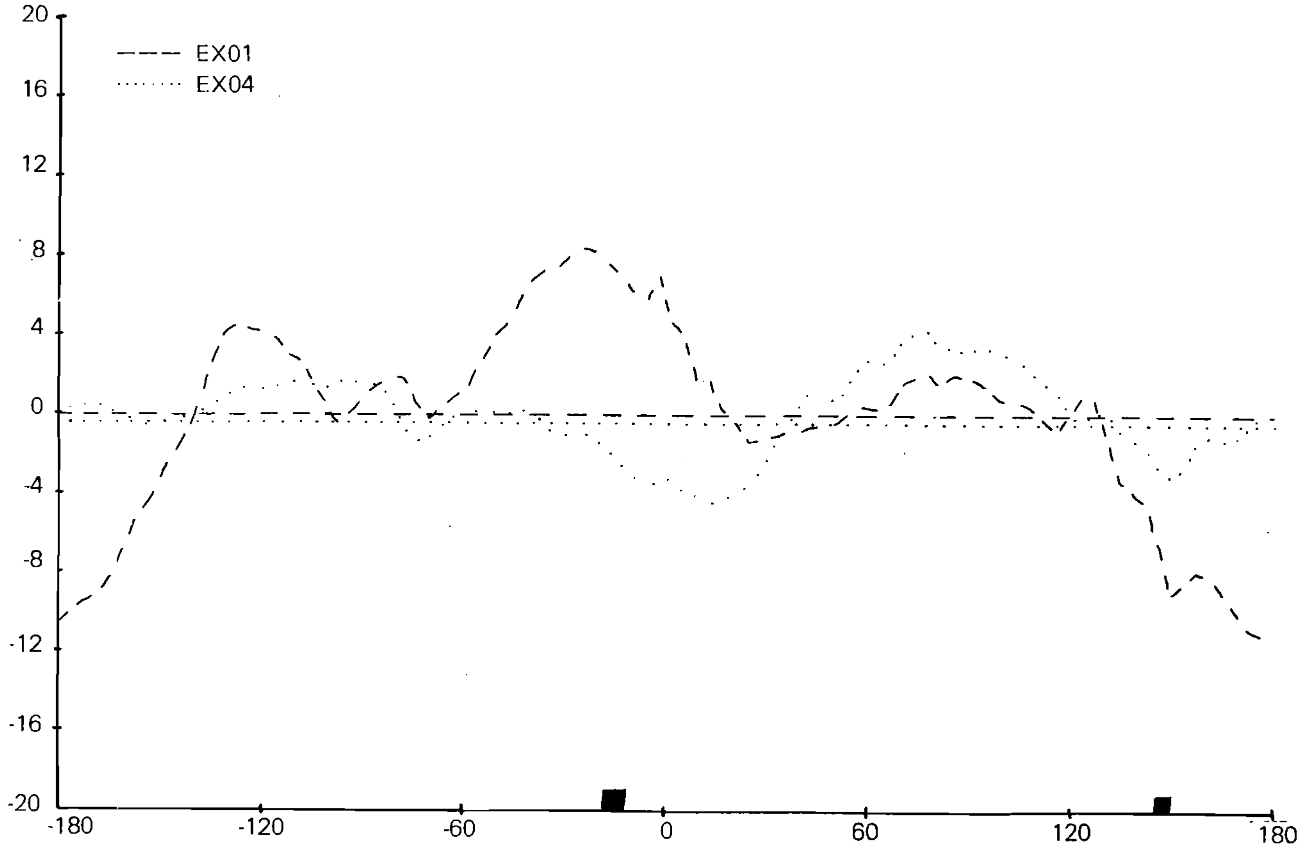

Figure 14. The differences in surface pressure between EX01, EX04 and the average of the three control cases along the latitude line 37.5^{0}N.

EX04, which have the same locations of energy parks but different amounts of waste heat release. The much larger changes in EX01 are clear. Over the Pacific park in EX01 there was a pressure decrease which is greater on the donwstream side of the park. In EX04 there is a much smaller pressure decrease, with its maximum slightly upstream of the park. Over Asia the differences in the two experiments are similar but elsewhere there are no similarities.

5. MODEL VARIABILITY

As pointed out in this and several earlier publications, an important aspect of the analysis of the results of sensitivity experiments is the evaluation of a signal-to-noise ratio. Thus, it is necessary to determine how much of the difference between a sensitivity experiment and control experiment(s) is due to the perturbation (in our case, waste heat) introduced and how much is due to the model's inherent variability.

If we consider two experiments run with a GCM in which the only difference between the initial conditions is a random small difference (for example, added to the initial wind field in the model, with a maximum amplitude of 1 $m \cdot sec^{-1}$), we find, by looking at the root-mean-square difference between the two experiments for a model variable (e.g. temperature) as a function of time, that the difference between the two experiments grow rapidly in the first 15 days, then more slowly and after 30 or 40 days the difference between the two cases varies about some mean value. This growth of small initial errors means that after about a week the local solutions of the GCM are indistinguishable from solutions selected at random from an ensemble of solutions under the same conditions.

This behavior is basically due to the *high degree of non-linearity present in the models*, whereby changes on even the very smallest scales are ultimately felt on all other scales. This uncertainty in the evolution of the solutions (i.e. the differences from an unperturbed case) is the inherent noise in the determination of climate statistics with such models. The models simulate the variability of the real atmosphere which is due to daily weatner fluctuations (see, for example, Madden 1976; Leith 1973).

It is important to have a good estimate of the noise level of the model so that the signal form a given perturbation to the model, e.g. the addition of waste heat, can be assessed. Methods for determining the natural variability usually rely on the comparison of an ensemble of control cases, which differ only by small random differences in initial conditions. The natural variability of the real atmophere can be determined from the many years of meteorological observations. The variability of the model atmosphere should ideally be determined from a large (30 or more) sample of control cases; in the absence of such information, best use must be made of the inforamtion from a limited number of control cases.

Murphy et al. (1976) and Williams et al. (1977) have estimated the variability of the Meteorological Office GCM used in the energy parks experiments by computing the standard deviations of 40-day means of meteorological variables in the three control cases. Figure 15 shows the standard deviation of the 40-day mean surface pressure field computed from the three control cases. The largest variability is over Siberia (s > 14mb). Figure 16 shows an estimate of the standard deviation of 40-day mean sea-level pressure computed from the data of Schumann and van Rooy (1952), from which it can be seen that the maximum observed standard deviation of sea-level pressure is about 8mb and occurs in the vicinity of the midlatitude low-pressure centers.

From sampling theory one can state that

$$S_T^2 = S^2/(T/T_0) \quad , \qquad (1)$$

where S_T^2 is the variance of a time average of length T, S^2 is the variance of daily values, and T_0 is the characteristic time between effectively independent sample values. Using (1) we can derive the relationship

$$S_{40}^2 = \frac{S_{10}^2}{4} \quad , \qquad (2)$$

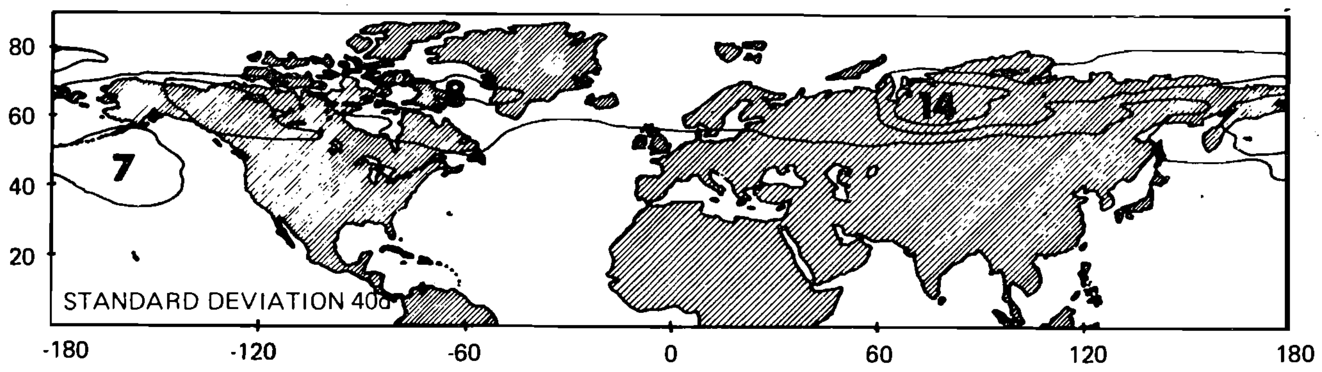

Figure 15. Standard deviation of the 40-day mean surface pressure field computed from the three control cases (contour interval 4 units).

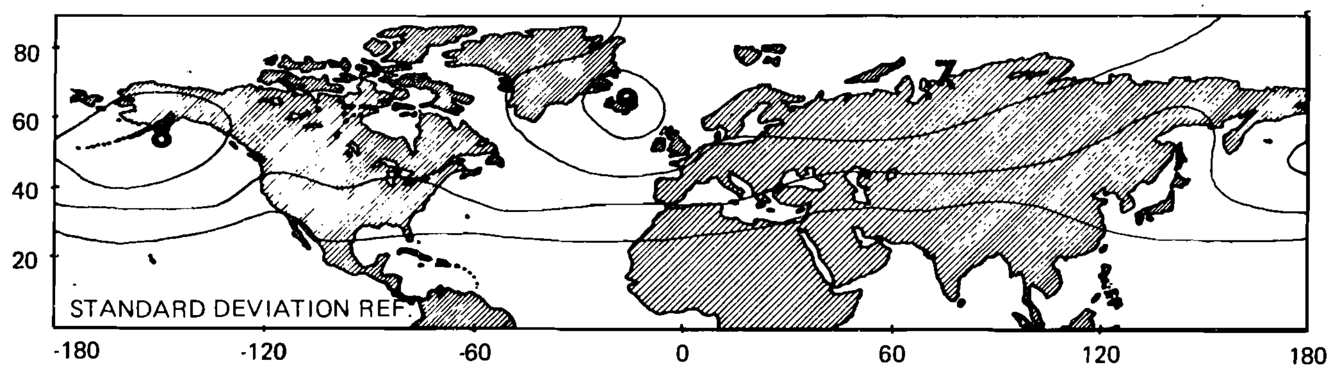

Figure 16. Estimate of the standard deviation of 40-day mean sea-level pressure computed from the data of Schumann and van Rooy (1952) (contour interval 2 units).

where S_{40}^2 is the variance of a 40-day mean and S_{10}^2 is the variance of a 10-day mean. It is therefore possible using (2) to estimate the variance of the 40-day mean using the information from twelve 10-day means. Figure 17 shows the standard deviation of the 40-day means computed from the twelve 10-day mean surface pressure values according to equation (2). The standard deviation over the Siberian area is now reduced to ≈ 9mb and the distribution is much smoother. The observed maximum standard deviation in the vicinity of the Aleutian Low is underestimated by the model, and the large variability in the vicinity of the Icelandic Low is not seen in the model results. The general underestimation of variability has been noted for other models and must be partly a result of the constant sea-surface temperature field used in the model compared with the observed variability of sea-surface temperature.

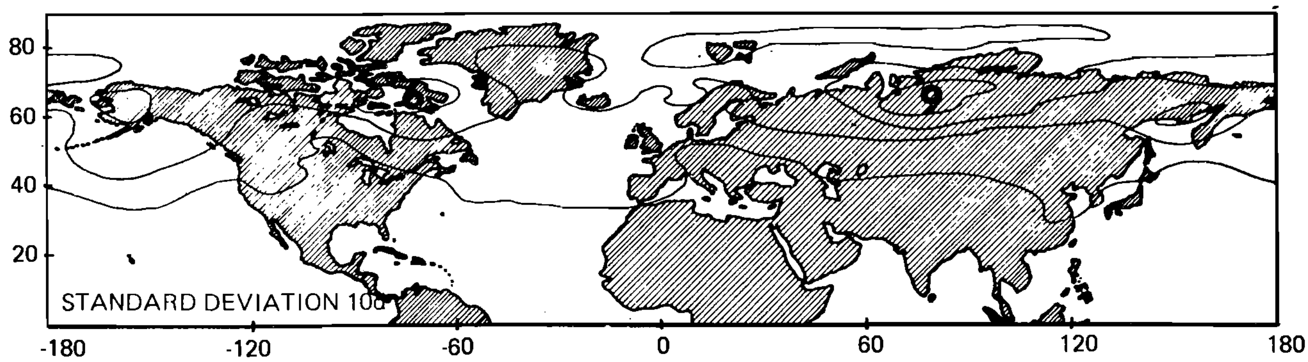

Figure 17. Standard deviation of the 10-day mean surface pressure field computed from the three control cases (contour interval 2 units).

The signal-to-noise ratios for different meteorological variables and each of the energy parks experiments have been recomputed using the revised estimates of the standard deviation of the 40-day mean. Figure 18 shows the ratio for the surface pressure field in EX01, which can be compared with the ratios computed from three 40-day means (see Murphy et al., 1976, Figure 11a). The distribution of large values of the ratios is not much changed. The values of the ratios based on 10-day means

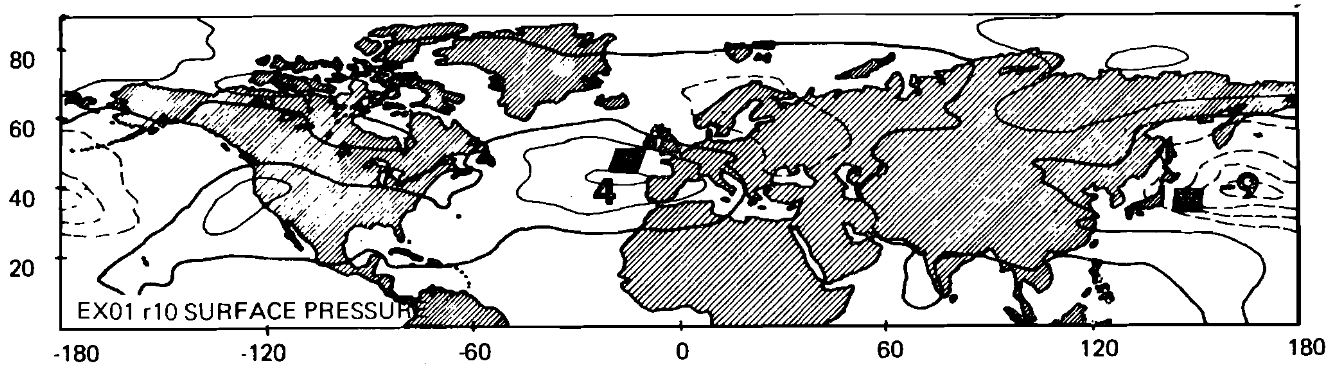

Figure 18. The ratio of the differences in surface pressure in EX01 to the 10-day standard deviation of that variable in the three control experiments (contour interval 2 units).

for temperature at $\sigma = 0.9$ in EX01 are shown in Figure 19. The ratios based on 40-day means are given in Murphy et al. (1976; Figure 13a in that report). It is clear that some areas which had very large values of the ratio when based on 40-day means (especially over northern Scandinavia, Siberia, and Labrador) do not have large ratios when 10-day means have been used. That is, the noise level was underestimated in these areas when 40-day means were used. Similarly for temperature at $\sigma = 0.9$ in EX02 (Figure 20), the ratios based on 10-day means do not have large values over the Great Lakes areas and Siberia.

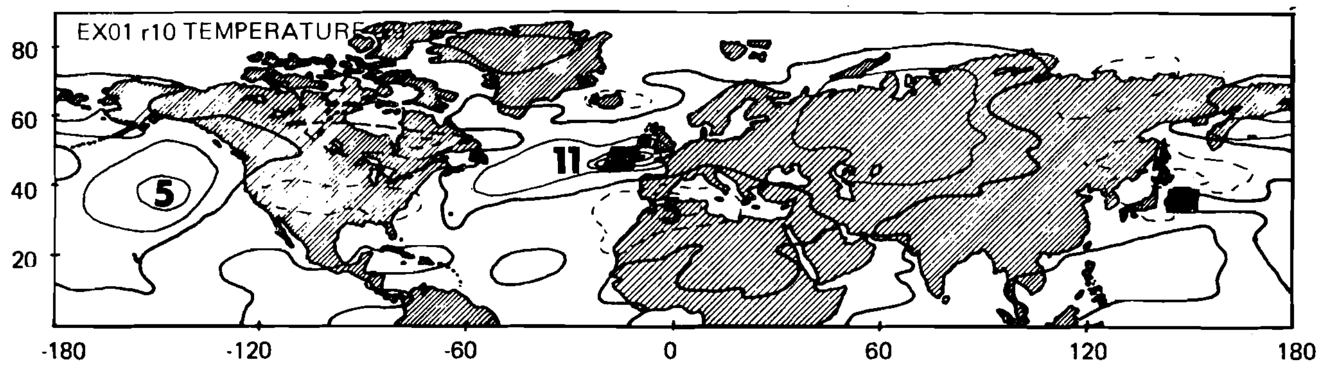

Figure 19. The ratio of the differences in temperature in the lowest layer of the model in EX01 to the 10-day standard deviation of that variable in the three control experiments (contour interval 2 units).

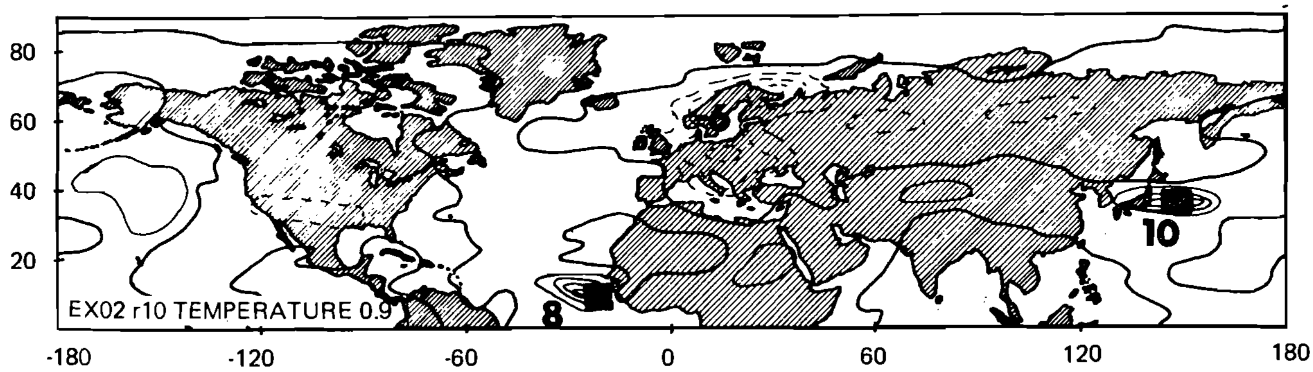

Figure 20. The ratio of the differences in temperature in the lowest layer of the model in EX02 to the 10-day standard deviation of that variable in the three control experiments (contour interval 2 units).

The ratios for surface pressure and temperature at $\sigma = 0.5$ in EX04 based on 10-day means are shown in Figures 21 and 22 respectively. In comparison with the ratios based on 40-day means (Figures 4 and 11d), the ratios for surface pressure based on 10-day means suggest that there is no statistically significant pressure increase on the upstream side of the Atlantic energy park (although, as discussed earlier, the occurence of this increase in other experiments and meteorological arguments would suggest that it has physical significance). The pressure decrease over the Mediterranean is also not statistically significant when compared with the new estimate of noise-level. Although there are still areas with large values of the ratio, the wide-spread occurence of a significant response to the energy parks in EX04 is not found. For temperature at $\sigma = 0.9$ there are some important differences between the two estimates of the signal-to-noise ratio. The large value of the ratio (+13) over Labrador is not found when the standard deviation is estimated from 10-day means, and in other areas the ratio is much smaller in the newer evaluation. This again points to the fact that the variability in temperature at $\sigma = 0.9$ was underestimated previously.

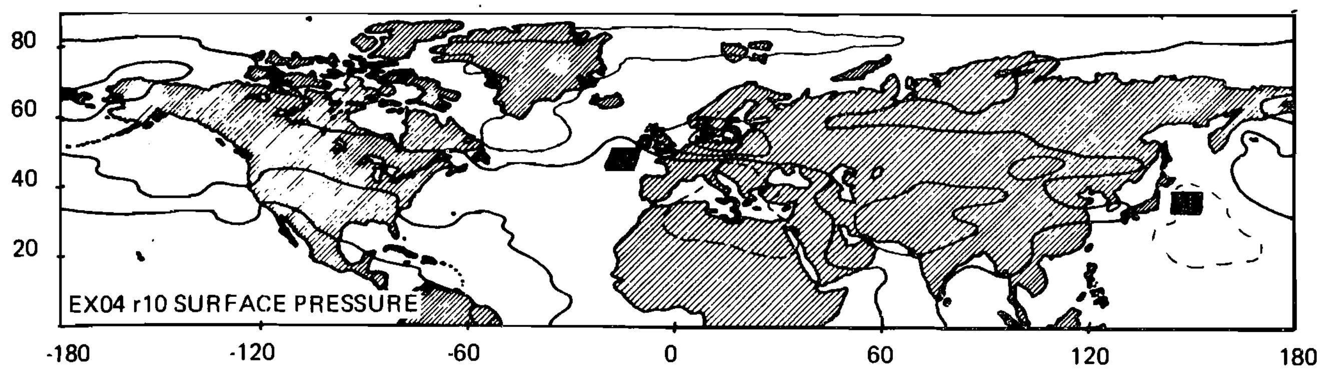

Figure 21. The ratio of the differences in surface pressure in EX04 to the 10-day standard deviation of that variable in the three control experiments (contour interval 2 units).

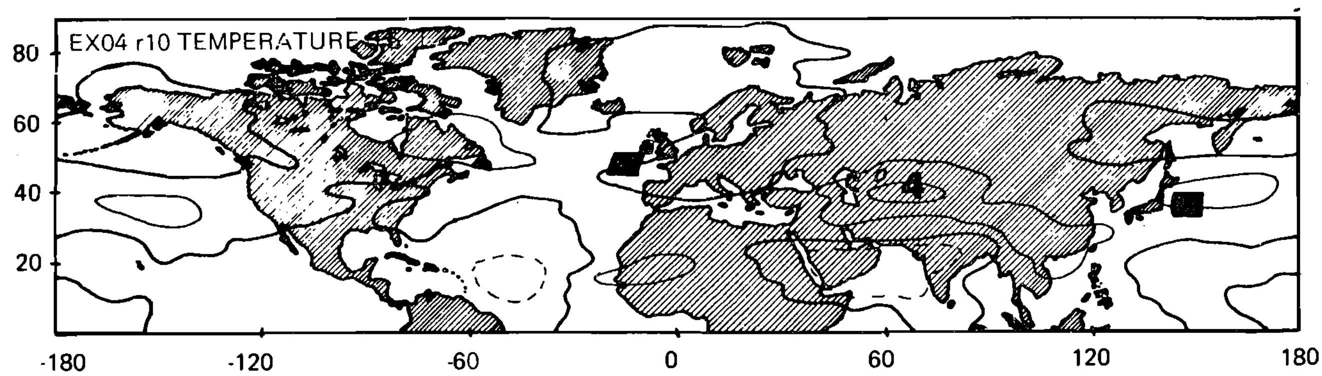

Figure 22. The ratio of differences in temperature at σ-level 0.5 in EX04 to 10-day standard deviation of that variable in the three control experiments (contour interval 2 units).

6. CONCLUSIONS

The fourth experiment with the Meteorological Office GCM has been performed to get further insight regarding the behavior of the simulated atmospheric circulation with different waste heat scenarios.

Emphasis has been given to the investigation of the non-linearity of the response of the simulated atmosphere. Results of EX04 show that there is still a response to the waste heat input but not as big as in EX01. Also of importance is the comparison between EX03 and EX04 because those two experiments involved the same amount of energy release into the atmosphere but the distribution of the heat islands differed. In EX03 there was only one energy park (west of England), whereas in EX04 the heat was released from both an Atlantic park and a Pacific park. The input from two parks produced a much different response than the input from a single energy park, although the same amount of energy was added to the system. EX04 shows clearly less changes than EX03 did. In addition, the changes in pressure and temperature distribution in the lowest layer of the model differ strongly not only from those in EX03 but also from those in EX01. This shows again the strong non-linearity of response of the atmospheric circulation. It should also be noted that the changes over the oceans are more similar than over the continents (in distribution and amount as well), but the changes are not necessarily in the same direction over all continental areas.

Otner investigations have concerned the influence of the heat release on higher levels of the atmosphere. Wind and temperature fields at σ level 0.5 for all experiments have been considered. The temperature changes at this level were found to be much smaller, but, as the variability is also smaller here, the values still remain statistically significant. Only in EX01 was the pattern the same at $\sigma = 0.5$ and $\sigma = 0.9$. Likewise, only in EX01 are the changes of T at $\sigma = 0.5$ still significant in the vicinity of the parks. In EX02, EX03, and EX04 the effect of the heat islands is concentrated at the surface and has not spread to higher levels.

Changes in the value of the west-east component of the wind at $\sigma = 0.5$ give some information regarding changes in, for example, the jet stream circulation, and it is very possible that the energy input in our experiments will also have had an influence on the circulation at $\sigma = 0.5$. Again, the highest and as well significant changes were found in EX01.

Finally, a better estimate for the model's inherent variability has been found, and the t-statistics have been recalculated. Previous results were confirmed with this calculation, and a much smoother distribution of ratios has been obtained avoiding unrealistically large values in some places.

Future plans might include another GCM experiment with a more realistic distribution of the released energy, but experiments with regional or meso-scale models would be very helpful for further investigation. Case studies of urban heat islands and other diagnostic studies will also be of value.

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