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

PART I

J. Williams
G. Krömer
A. Gilchrist[1]

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[1] Meteorological Office, Bracknell, Berkshire, UK

PREFACE

The IIASA Energy Program is studying global aspects of energy systems in terms of resources, demands, options, strategies, and constraints. One constraint on an energy system is represented by its impact on climate. A recent IIASA Research Memorandum (RM-76-79) described two experiments with a numerical model of climate, which investigated the impact of waste-heat release from large-scale energy parks on the simulated atmospheric circulation. This report describes a further experiment made with the same model and compares the results with those of the first two experiments.

In addition a further analysis tool, that of zonal harmonic analysis, has been applied to the results of all three energy parks experiments. Further experiments, suggested by the results of the first three experiments, will be made.

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SUMMARY

The general circulation model (GCM) of the United Kingdom Meteorological Office (UKMO) has been used to investigate the impact of an input of waste heat (1.5×10^{14}W) into the atmosphere in a small area in the mid-latitude eastern Atlantic Ocean. The results of this experiment have been compared with those of two earlier experiments in which the waste heat was input from two energy parks, one in the Atlantic and one in the Pacific Ocean.

The energy park produced significant responses in the surface pressure field, the temperature in the lowest layer of the model, and in the total precipitation distribution. The changes are of the same order of magnitude as the changes found in two earlier energy parks experiments, and there are some similarities between changes in this experiment and EX01, especially over the area immediately downstream of the energy park.

The results of all three energy parks experiments have been investigated using zonal harmonic analysis, and the influence of the energy parks on the positions and amplitudes of waves in the temperature and wind fields are discussed.

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Part I

1. INTRODUCTION

About two years ago the IIASA Energy Program began to study the possible impacts of energy systems on climate. This 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 to conduct these studies.

A recent IIASA Research Memorandum (RM-76-79, Murphy et al., 1976) described the setting up and running of the first two experiments. In both experiments there were two energy parks, each of which added 1.5×10^{14} W to the atmosphere. In the first experiment (EX01), the parks were located in the North Atlantic southwest of England, and in the North Pacific east of Japan; in the second experiment (EX02), the energy park in the Pacific was in the same location, but the one in the Atlantic was located west of Africa.

The use of numerical models to simulate climate and investigate its sensitivity to different perturbations was described by Murphy et al. (1976). 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) for 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. Therefore, despite their recognized 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. In particular, the sensitivity experiments may indicate the changes to be expected even if the basic state is not simulated perfectly.

In the following paragraphs we will describe the results of a third energy parks experiment, and we will compare these results with the three control cases from the model and with the earlier two energy parks experiments.

2. THE THIRD IIASA-UKMO ENERGY PARKS EXPERIMENT

2.1 The UKMO General Circulation Model

The original form of the model is described by Corby et al. (1972). The version used in this project is the same as that described by Rowntree (1975). Major features of the model are given by Murphy et al. (1976). We have used the hemispheric version of the model, which has five levels in the vertical, equally spaced in terms of pressure at sigma values of 0.9, 0.7, 0.5, 0.3, and 0.1 (sigma value = pressure/surface pressure). The gridpoints are nearly equally distributed with a grid length of approximately 330 km. Prescribed boundary conditions include the earth's orography, the incoming solar radiation, albedo, cloud amounts, and sea-surface temperatures, which are fixed at seasonal average values.

2.2 Scenario of EX03

The IIASA-UKMO experiments (Murphy et al., 1976) 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 we designate each park with a letter, then in the first three energy parks experiments we have used three parks with the following locations:

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

At each park the heat input was 1.5 x 10^{14} W. Figure 1 shows the locations of these three parks.

In EX01 the impact of a combination of parks A and C was investigated; i.e. one park in the mid-latitude Atlantic and one in the mid-latitude Pacific.

In EX02 the impact of a combination of parks B and C was investigated; i.e. the same park in the Pacific Ocean plus a tropical Atlantic Park.

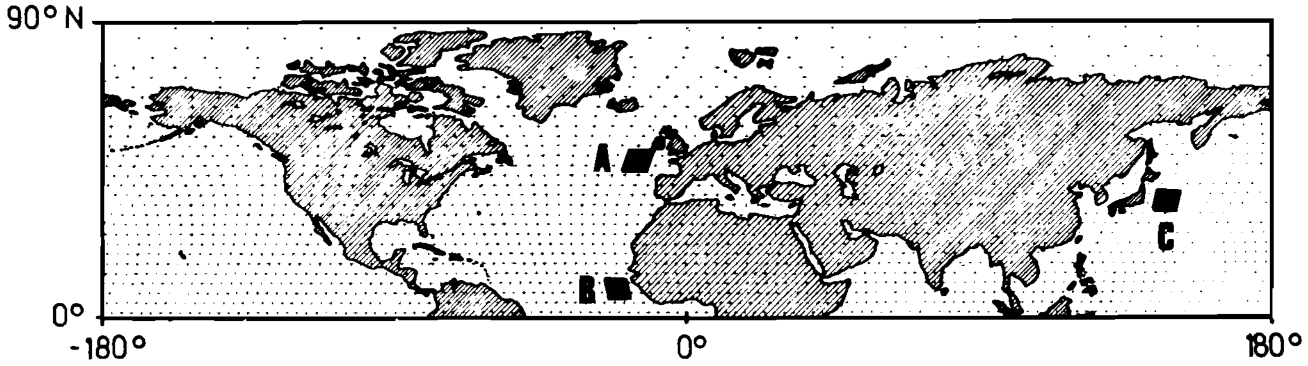

Figure 1. Locations of the three energy parks.

In EX03 the impact of park A alone was investigated; i.e. a park, putting 1.5 x 10^{14} W into the atmosphere, situated in the mid-latitude Atlantic. It should therefore be noted that the input of heat into the atmosphere from the energy park(s) is half as much in EX03 as in EX01 and EX02.

As pointed out by Murphy et al. (1976) the energy parks have not been 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 the heat by ocean currents and, therefore, would require a linked atmosphere-ocean model. The simplifications introduced were, therefore:

(i) to make the area of a park equal to four grid boxes in the model;

(ii) to insert all the heat directly into the atmosphere in sensible form.

To simulate the parks, 375 Wm^{-2} was added to the sensible heat exchange routine of the model at the four grid points within each park. The total amount of heat added in EX01 and EX02 was 3 x 10^{14} W, the same amount as added in other experiments made by Washington (1972) with the NCAR model, and based on Weinberg and Hammond's (1971) figures of a per capita energy usage of 15 kW and an ultimate population of 20 billion. This is, however, an unrealistically large input of heat compared with present estimates of future energy usage and population levels. In EX03, the total heat input is half of that in the first two experiments (i.e. 1.5 x 10^{14} W) but is concentrated at one energy park instead of two.

In addition to the three energy parks experiments, we have three control cases made with the same version of the model. These control cases simulate unperturbed January climate and differ from each other only as a result of small random differences in the initial conditions. The energy parks experiments are also run with January boundary conditions. Each experiment is a simulation of 80 model days, and the results are generally described in terms of means of meteorological variables for days 41-80.

2.3 Results of EX03

Figure 2 shows the difference between the surface pressure field in EX03 for days 41-80 and the average of the three control cases. As was the case with the first two energy parks experiments, we see large coherent areas of pressure change.

Over the park itself there is a very small pressure decrease, while over the Atlantic generally there is a rise with a maximum value of about eight mb. Downstream over Western Europe there is a pressure fall (up to 11 mb), and over most of the Soviet Union there is a pressure increase of up to 29 mb. Over North America there is a pressure decrease centered over Alaska.

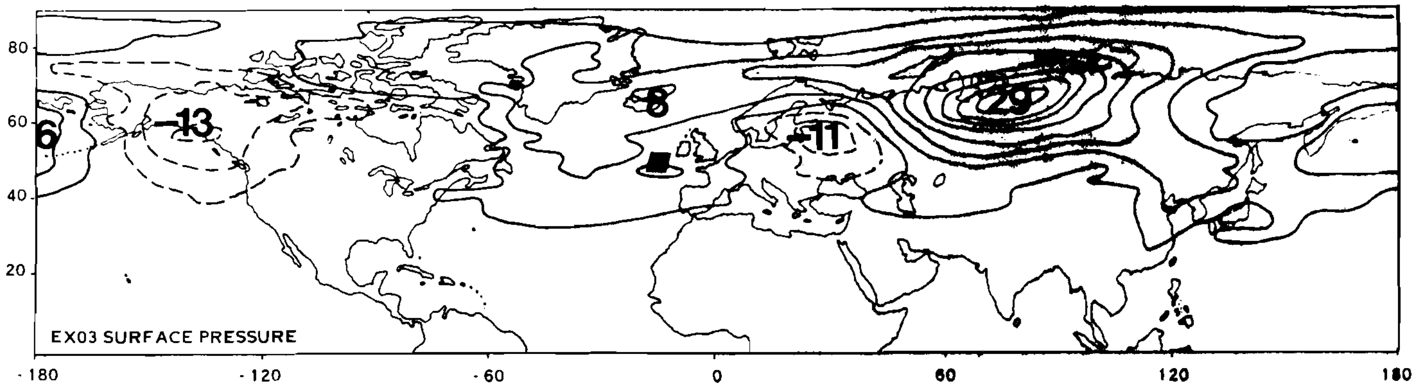

Figure 2. The differences in 40-day mean surface pressure between EX03 and the average of the three control experiments (contours at every 4 mb).

Comparing these patterns with the equivalent differences computed for EX01 and EX02, we notice first of all that the response over the park in EX03 is different from that in the earlier experiments. In EX03, the Atlantic energy park has produced a local surface pressure change of opposite sign to the pressure change over a larger area upstream and downstream, while the surface pressure change in EX01 over the Atlantic park was coherent with that over the surrounding area. It might be important to note, however, that the pattern of change in the vicinity of the parks is quite similar, although the levels are different in the two experiments. In terms of the magnitude of the surface pressure changes we may conclude that the changes in EX03 are of the same order as those in EX01. Over Europe, the area immediately downstream of the Atlantic energy park, there is qualitatively a lot of similarity between the changes in EX01 and the changes in EX03. For example, over the Baltic region both experiments show a decrease of surface pressure. The large pressure rise over Siberia is also found in both experiments. In detail, however, when we subtract the surface presssure field in EX03 from that in EX01, we see that the different locations of the centers of pressure increase and decrease lead to quite large differences between the experiments (Figure 3). For example, the decrease of pressure over the Baltic region extends much further north and further east and west in EX01 than EX03, while the increase of pressure over Siberia is further east in EX01 than EX02. Consequently, the computed difference between the experiments amounts to 32 mb over western Siberia. Since the pressure near the Atlantic energy park was

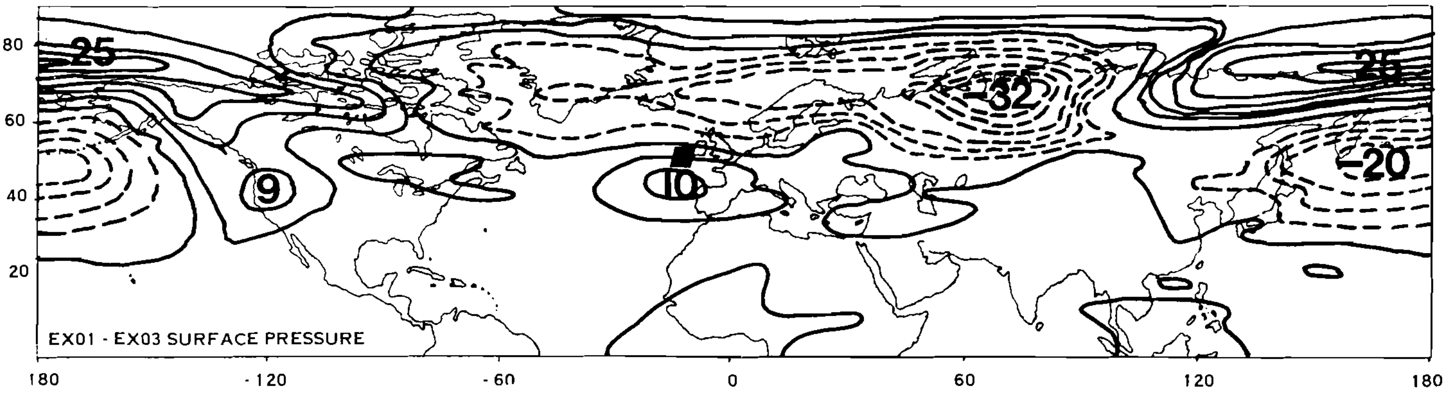

Figure 3. The differences in 40-day mean surface pressure between EX01 and EX03 (contours at every 4 mb).

increased in EX01 but hardly changed in EX03, there is a ten mb difference between the experiments in the vicinity of the park.

While the surface pressure results for EX01 and EX03 are qualitatively similar immediately downstream of the Atlantic energy park, they are quite different in the Pacific area. In EX01 the surface pressure decreased by up to 14 mb over the Pacific, while in EX03 there is a pressure increase, compared with the average of the control cases, of 6 mb. Likewise, over North America, Greenland, and the western North Atlantic the patterns are different in the two energy parks experiments. Since both experiments have an Atlantic energy park, qualitative similarities are not unexpected immediately downstream of the park, but the absence of a Pacific energy park in EX03 results in a different response there and downstream. Comparison of the surface pressure field in EX03 with that in EX02 shows that there is little similarity in response.

As in the evaluation of EX01 and EX02 the question must be asked: How much of the difference between EX03 and the average of the three control cases is due to the inclusion of the energy park, and how much is due to the natural inherent variability of the model? Using the same method as Murphy et al. (1976), the ratio of the absolute value of the difference to the standard deviation of the variable in the three control experiments, has been computed. This ratio has a Student's t-distribution with two degrees of freedom, and values of the ratio greater than 5 are statistically significant at the 0.05 level. That is, if the ratio for the variable under consideration is greater than 5 at a particular grid point, there is a 95 per cent chance that the difference between the energy park exper-

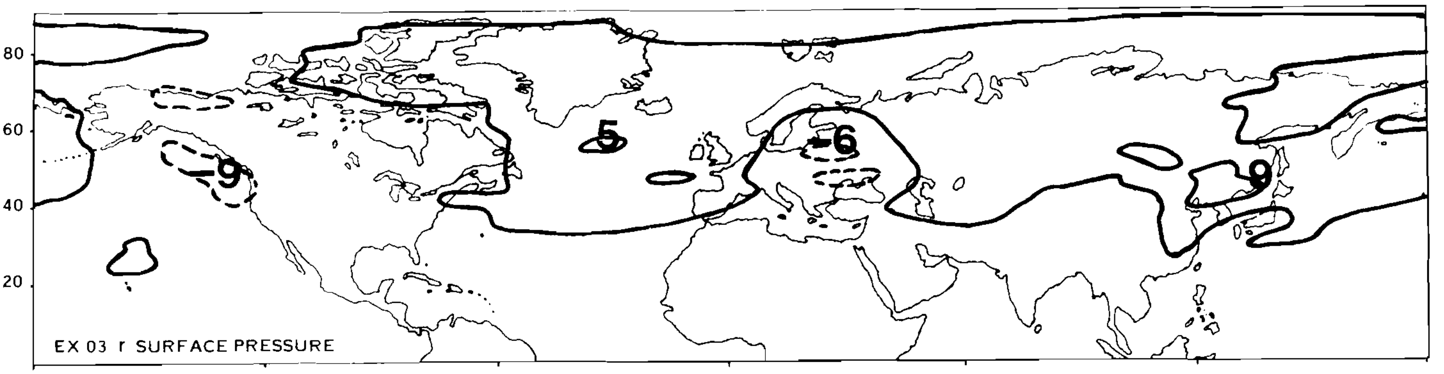

Figure 4. The ratio of the differences in surface pressure in EX03 to the standard deviation of that variable in the three control experiments (contour interval four units).

iment and the average of the controls is due to a response to the energy park and not to the inherent variability of the model.

Figure 4 shows the values of this ratio for surface pressure for EX03. There are four areas over which the change in surface pressure from the average of the control cases to the EX03 can be ascribed to the inclusion of the energy park. These areas are: upwind of the park over the Atlantic Ocean; over central Europe; over the Japan and China area; and, over Alaska and western North America. Unlike the distribution of signal-to-noise ratio in EX01 and EX02, there is no statistically significant pressure change over the park itself, although the small pressure decrease can be understood in physical terms. Comparison of Figure 4 with similar figures produced for EX01 and EX02 (Murphy et al., 1976, ibid Figure 11), suggest that the area of significant pressure change is at least as large in EX03 as in earlier experiments, indeed certainly larger than in EX02. In EX01, significant changes in the surface pressure field were over and upstream of the Atlantic park over and downstream of the Pacific park. There was no significant change over North America as there is in EX03. In EX02, the only significant change not over the energy park was over western Europe, whereas in EX03 there are four areas in the middle latitudes other than over the energy park, where large values of the signal-to-noise ratio occur.

Figure 5 shows the differences in the temperature field at $\sigma = 0.9$ between EX03 and the average of the three control cases. As in the earlier experiments, it is not suprising to

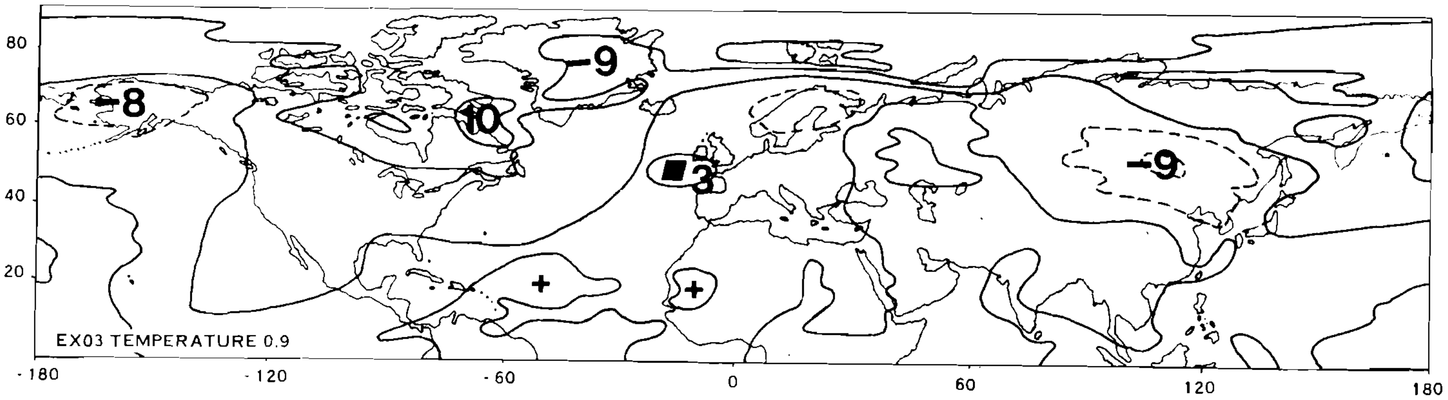

Figure 5. The differences in 40-day mean temperature (^{0}C) in the lowest layer of the model between EX03 and the average of the three control experiments (contours at every 4^{0}C).

find that the temperature in the lowest layer of the model increased in the immediate vicinity of the energy park in EX03. In this case it increased by 3^0C, a smaller value than found over the parks in EX01 and EX02.

As was found above for the surface pressure changes, the response on a local scale is of opposite sign to the response over the larger surrounding area. Over western Europe there is a temperature decrease, over western USSR and eastern Europe the temperature increases by up to 7^0C, and over the eastern USSR and China there is a temperature decrease (maximum -9^0C). Over North America there is a temperature increase with a maximum of 10^0C centered over the eastern Canadian Arctic and a temperature decrease over Alaska.

Comparing the temperature changes in EX03 with those in EX01 and EX02, one finds that there are not many similarities. For example, in EX01 and EX02 the temperature decreased over North America while in EX03 it increased. The changes over Eurasia in EX03 are distributed in smaller areas than in the earlier experiments. The magnitudes of the temperature change are, however, of the same order in EX03 as in EX01 and EX02.

The different temperature responses (at $\sigma = 0.9$) in EX01 and EX03 are further illustrated in Figure 6. Over much of Eurasia and the Pacific EX01 is warmer than EX03, while over North America and the Arctic EX01 is colder than EX03. All of the large differences are in the middle and high latitudes, with only small differences between EX01 and EX03 in the tropics.

Figure 7 shows the values of the signal-to-noise ratio for temperature at $\sigma = 0.9$ for EX03. The temperature increase over the energy park is seen to be a result of the inclusion of the energy park and, as found before, there are significant responses over other areas of the hemisphere. There is an extremely large value of the ratio centered over Scandinavia, and further significant values are found over Indonesia, Greenland, the north-east of North America, and over Alaska. The distribution of the ratios for EX03 bears some similarities with those for EX01 and EX02, in particular the change over the Great Lakes area is similar in each experiment--this is presumably a result of a small model variability in this area, which is then reflected in the large signal-to-noise ratio in each map. The large value of the ratio over Scandinavia for each experiment presumably also has the same cause.

Figure 8 shows the difference in precipitation between EX03 and the average of the three control cases. In the middle and high latitudes the differences are not large, and it is only in tropical latitudes that we find large changes. This was also the case in EX01 and EX02 (Murphy et al., 1976, ibid Figure 10), and it was pointed out that precipitation in

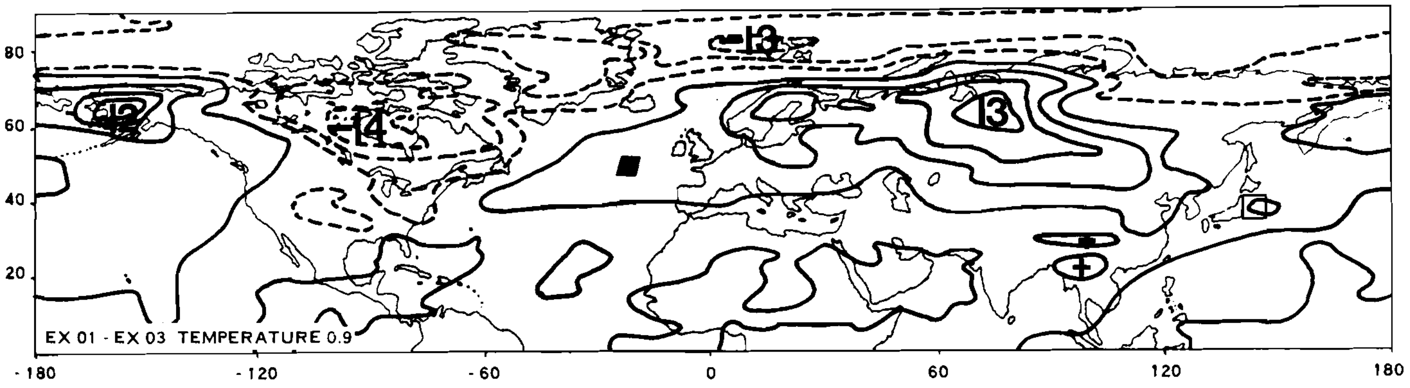

Figure 6. The differences in 40-day mean temperature in the lowest layer of the model between EX01 and EX03 (contours at every 4°C).

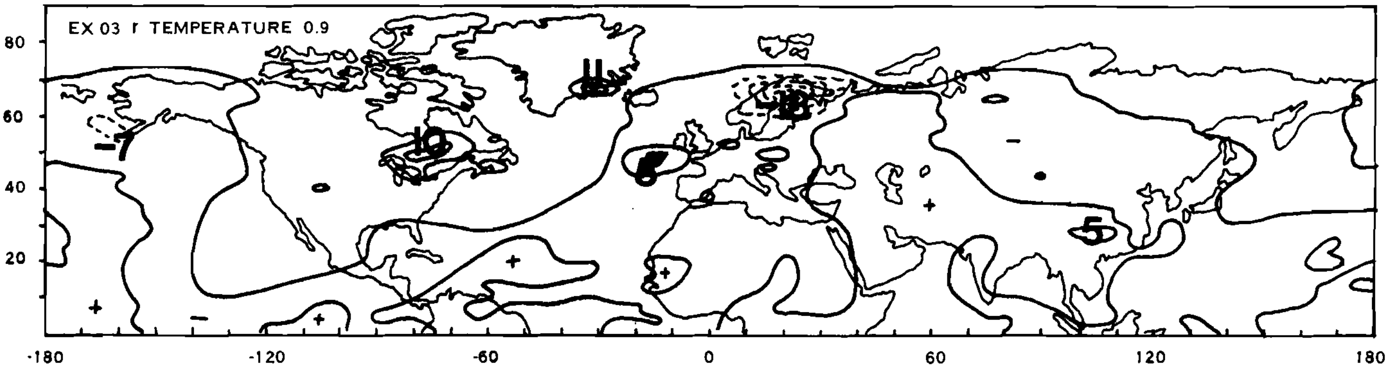

Figure 7. The ratio of the differences in temperature in the lowest layer of the model in EX03 to the standard deviation of that variable in the three control experiments (contour interval four units).

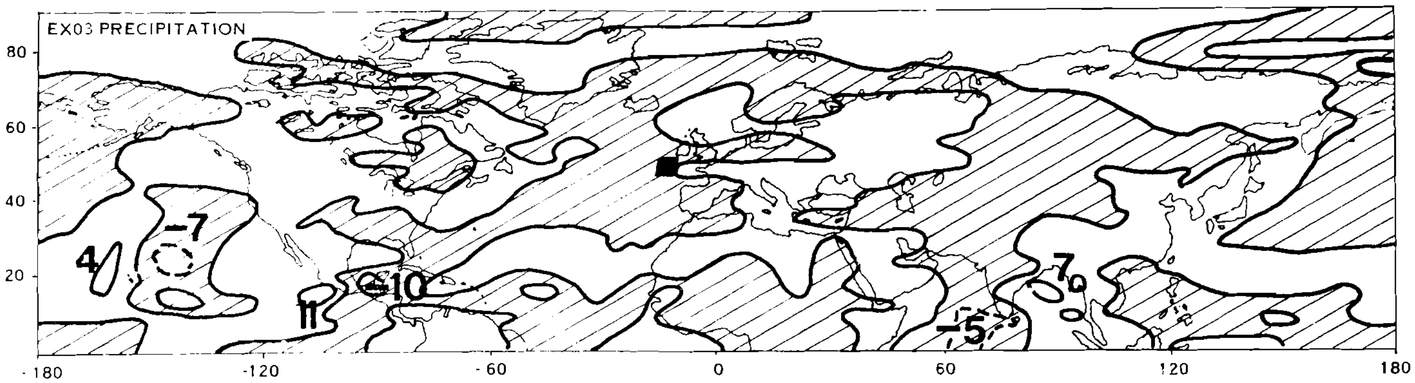

Figure 8. The differences in 40-day mean total precipitation (in mm/day) between EX03 and the average of the three control experiments (contours at every 4 mm/day).

the tropics is primarily a result of instabilities in the vertical, so that there is a tendency for rain, once initiated at a grid point, to persist because of small-scale dynamical interactions. For this reason we see in tropical latitudes some grid points at which large precipitation changes have occurred. The precipitation differences shown in Figure 8 are of the same order of magnitude as those in EX01 and EX02.

Figure 9 shows the differences in precipitation between EX01 and EX03, which emphasises the fact that differences in middle and high latitudes are small, while large differences at individual grid points in the tropics do occur.

As pointed out by Murphy et al. (1976) the distribution of daily rainfall amounts, particularly in the tropics, is highly skewed; consequently the assumption of normality, which is required for the application of significance tests to the t-statistic, probably does not hold. It is therefore not possible to ascribe probabilities of significance to the precipitation ratios. It should be noted, however, that a large value of the ratio does occur in the vicinity of the Atlantic energy park in EX03, and large values were also noted in EX01 and EX02 near the parks. Other large values of the ratio occur particularly in the tropics, where they have a scattered distribution.

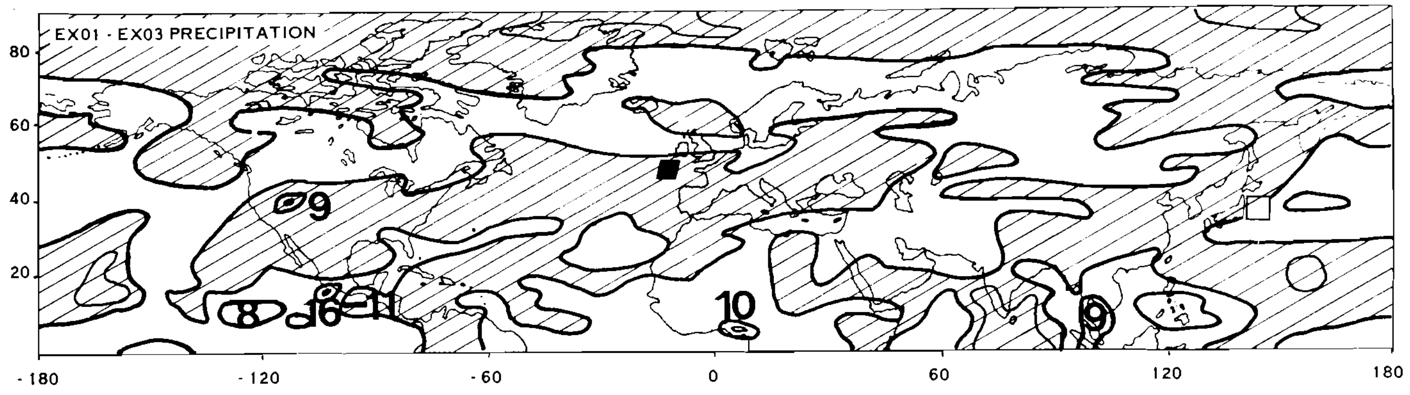

Figure 9. The differences in 40-day mean total precipitation between EX01 and EX03 (contours at every 4 mm/day).

2.4 Discussion

An experiment has been made with the UKMO general circulation model to investigate the impact of an energy park (1.5×10^{14} W) in the Atlantic Ocean on the model atmosphere. The park produced significant responses in the surface pressure field, which qualitatively resemble the pressure response found in EX01 downstream of the Atlantic park. The computation of signal-to-noise ratios for the temperature and pressure fields points to the deficiencies engendered by the fact that we are using only three control cases for the evaluation of the model variability. The signal-to-noise ratios for temperature at $\sigma = 0.9$ are similar in certain areas in EX01, EX02, and EX03; for example, all three experiments have high values of the ratio over the Great Lakes area but quite different values of the temperature differences between the perturbed case and the average of the control cases. This is, therefore, one area where the standard deviation of the three control cases is very small, and the ratio comes out large for all perturbation cases. The small value of standard deviation in this area is a result, probably, of the small sample used for its computation.

In order to get a better estimate of the standard deviations of the different variables, the ideal solution would be to have a much larger sample (say 30) of control cases. This is not an acceptable solution because of the computer time and money required. So the other possibility is to make better use of the data available. Since we can assume that the characteristic time between effectively independent sample values is less than ten days, a better estimate of the standard deviation should be obtained on the basis of 12 10-day means instead of the three 40-day means presently used. This approach is being examined at present.

So far the results of the experiments have been considered only in terms of variables at or near the surface of the model atmosphere. It is also of interest to consider the impacts of the waste heat on higher levels of the atmosphere, particularly at the 500 mb level. We shall therefore evaluate the changes in the temperature and wind fields at $\sigma = 0.5$ in a subsequent report.

3. ZONAL HARMONIC ANALYSIS OF PRESSURE, TEMPERATURE, AND WIND FIELDS OF IIASA-UKMO ENERGY PARKS EXPERIMENTS

3.1 Introduction

If one considers a chart of the height of the 500 mb pressure surface, such as that illustrated for January in Figure 10, it is seen that the contours do not parallel the lines of latitude, but rather that there are significant variations in the zonal flow (that is, the flow in a direction around a latitude circle). In Figure 10 there are troughs at 80°W and at 140°E, and a weaker trough at 10°E to 60°E. These deviations--or waves--in the pressure surface are a result of features of the earth's surface. One cause of the waves is the presence of mountains, while a second cause is the difference in thermal effects of land and sea. The relative roles of these two causes have been frequently discussed by meteorologists in the last 30 years (see for instance, Palmen and Newton, 1969).

Maps of surface temperature and temperature and wind at about 500 mb likewise show waves around latitude circles, and these variables will be discussed in the present report. Since the surface pressure field waves are predominantly the result of the presence of mountains, the results of harmonic analysis of this variable are difficult to interpret and therefore not included. An objective method for comparing the waves from one map to another is to perform zonal harmonic analysis on the pressure or temperature fields for individual latitude circles, and thus describe the variations from the zonal (i.e. latitude) mean in terms of the amplitude and phase (i.e. position) of the different wave numbers.

van Loon et al. (1973) have performed zonal harmonic analysis on observed atmospheric pressure-height data; they show, for example, that in January at 500 mb at 50°N the combination of waves 1, 2, and 3 explains 96.2 per cent of the deviation from the zonal mean. That is, most of the variation from the zonal mean is explained by long waves. In this report we will discuss the results of zonal harmonic analysis of the 40-day mean temperature (T) at σ levels (where σ = pressure/surface pressure) 0.9 and 0.5, and the north-south component of the wind (v) at σ level 0.5, for the control cases and the energy

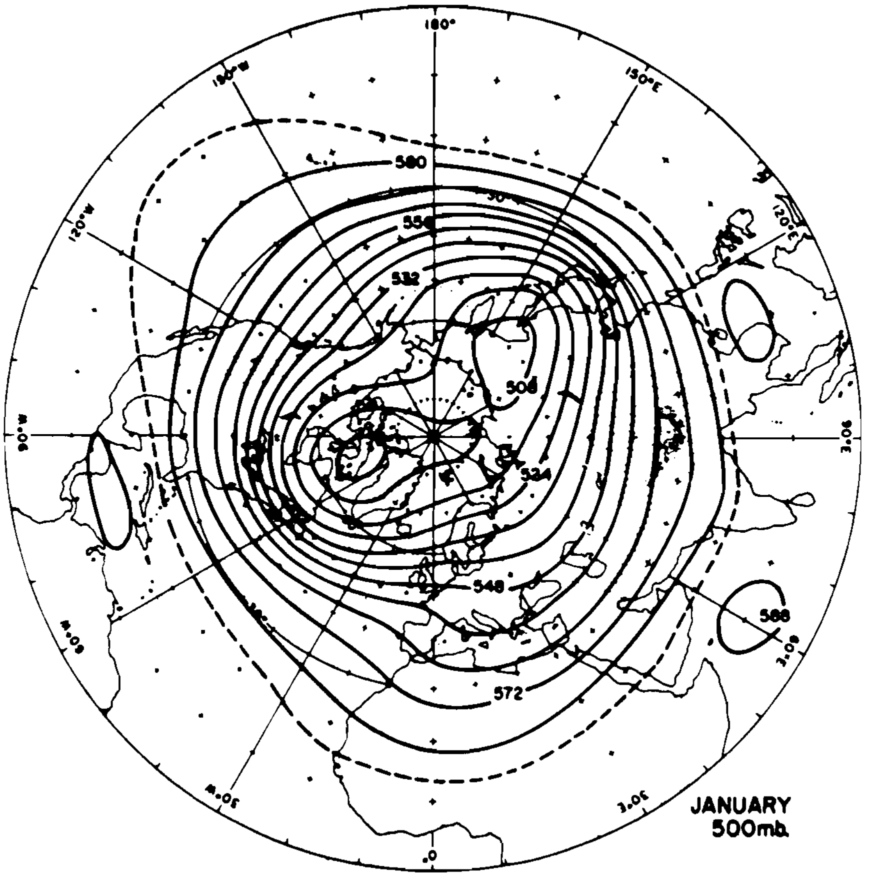

Figure 10. Mean 500 mb contours in January for the northern hemisphere (from Palmen and Newton [1969]).

parks experiments EX01, EX02, and EX03. The waves will be considered in terms of their amplitudes (in ^{0}C for temperatures, and m·sec^{-1} for wind), phase (in degrees, where the value given in the longitude of the first ridge east of the Greenwich meridian), and the percentage of the deviation from the zonal mean which is explained by the wave. Waves at latitudes 58.5^{0}N, 43.5^{0}N, and 31.5^{0}N will be considered.

3.2 Harmonic Analysis of the Temperature Field at $\sigma = 0.9$

Table 1 shows the amplitude, phase, and variance explained by waves 1 to 4 in the energy parks experiments, control cases, and difference maps at 43.5^{0}N. The waves do not show large variations in location (i.e. phase) from one experiment to another. Wave 2 explains more of the variance from the zonal mean than waves 1 and 3, and this relationship does not change between experiments. In EX01, the amplitude of the first four

Table 1. Harmonic analysis of the temperature field at $\sigma = 0.9$, 43.5°N.

	Wave 1	Wave 2	Wave 3	Wave 4
Average of 3 Control Cases				
Amplitude (°C)	6.2	9.0	3.0	3.5
Phase (°)	300	14	77	65
Variance (%)	26.0	56.0	6.0	8.2
EX01				
Amplitude (°C)	6.8	9.8	5.3	3.8
Phase (°)	311	19	77	65
Variance (%)	23.5	49.2	14.6	7.4
EX02				
Amplitude (°C)	5.8	8.7	5.0	3.5
Phase (°)	294	13	79	66
Variance (%)	21.9	49.2	16.0	7.8
EX03				
Amplitude (°C)	8.3	9.8	4.4	4.9
Phase (°)	297	17	66	65
Variance (%)	31.7	44.2	9.0	10.8
EX01 Minus Average of 3 Controls				
Amplitude (°C)	1.4	1.8	2.4	0.4
Phase (°)	11	48	77	61
Variance (%)	16.5	24.4	45.2	1.0
EX02 Minus Average of 3 Controls				
Amplitude (°C)	0.7	0.4	2.1	0.2
Phase (°)	177	123	81	87
Variance (%)	7.5	2.6	69.3	0.7
EX03 Minus Average of 3 Controls				
Amplitude (°C)	2.2	1.3	2.5	1.4
Phase (°)	289	41	53	64
Variance (%)	29.6	10.1	39.4	11.8

waves is greater than in the average of the three control cases. The amount of variance explained by wave 3 is increased, while that explained by waves 1, 2, and 4 is less than in the control cases. Likewise, in EX02 the amount of variance explained by wave 3 has increased. This is emphasized in the values given in Table 1, where we see that the harmonic analysis of the difference maps shows that wave 3 is dominant in the differences between EX01 and EX02 and the average of the controls. In EX03, the amount of variance explained by wave 2 is smaller than in the control cases and wave 1 is much bigger. Small increases in the amount of variance explained by waves 3 and 4 are also observed. For the differences between EX03 and the control cases, wave 1 explains more variance than it did in the differences for the first two experiments and wave 3 is still important, but not as large as in the first two experiments.

The characteristics of the waves at the other two latitudes are not given in tabular form. At latitude 58.5°N, the waves again shows no large differences in location between experiments. In EX01, wave 2 explains the largest amount of the variance from the zonal mean, in contrast to the control cases and EX02 and EX03 where wave 1 explains most of the variance. In EX02, the waves do not differ from those in the control cases at 58.5°N. In EX03, the amplitude of wave 1 is much greater than in the other experiments, while the amplitudes of the other waves are decreased.

At 31.5°N the waves in the surface temperature field have about the same phase in each experiment, and there are no substantial differences in the percent of variance explained by the waves in any of the experiments.

3.3 Harmonic Analysis of the Temperature Field at $\sigma = 0.5$

Table 2 shows the characteristics of the waves at 43.5°N for the temperature field at $\sigma = 0.5$ (about 500 mb). Again there are no large shifts in the positions of the waves from one experiment to another. In EX01, the amplitude of and the per cent variance explained by wave 1 is much larger than in the control cases, while wave 2 is smaller, wave 3 is amplified, and wave 4 a bit smaller. In EX02, there are no major changes in the amount of variance explained by the waves, waves 1 and 4 explain less variance, and waves 2 and 3 more variance than they do in the control and other cases, wave 4 is also amplified, while waves 1 and 2 explain less variance.

Harmonic analysis of the difference maps shows that, for EX01 and EX02, the difference between the energy parks experiment and the control cases is explained by waves 1 and 3. For EX03, the variance of difference field is mostly explained by wave 3 (65 per cent).

Table 2. Harmonic analysis of the temperature field at $\sigma = 0.5$, 43.5°N.

	Wave 1	Wave 2	Wave 3	Wave 4
Average of 3 Controls				
Amplitude (°C)	3.1	4.8	1.4	2.0
Phase (°)	191	6	61	60
Variance (%)	21.9	53.7	4.3	9.6
EX01				
Amplitude (°C)	5.5	4.4	2.8	2.3
Phase (°)	300	12	75	57
Variance (%)	45.0	28.3	11.3	7.6
EX02				
Amplitude (°C)	2.6	5.2	1.9	2.1
Phase (°)	270	3	69	55
Variance (%)	14.5	57.4	7.5	9.2
EX03				
Amplitude (°C)	3.1	5.0	2.8	2.7
Phase (°)	281	5	58	62
Variance (%)	17.9	46.3	14.8	13.1
EX01 Minus Average of 3 Controls				
Amplitude (°C)	2.5	1.1	2.0	0.5
Phase (°)	312	67	84	42
Variance (%)	53.3	9.2	33.9	2.4
EX02 Minus Average of 3 Controls				
Amplitude (°C)	1.1	0.6	0.9	0.7
Phase (°)	165	156	84	36
Variance (%)	38.9	12.3	24.7	16.7
EX03 Minus Average of 3 Controls				
Amplitude (°C)	0.6	0.2	1.5	0.7
Phase (°)	198	106	56	67
Variance (%)	9.2	1.4	65.1	13.3

At latitude 58.5^{0}N, there are some variations of the phase of the waves, especially wave 3; however, since the phase varies quite considerably between the control cases (between 77^0 and 94^0) it is hard to attribute changes of the phase wave 3 to the introduction of the energy parks. In the energy parks experiments, wave 3 explains more of the variance from the zonal mean than it does in the control cases but wave 3 is still smaller than waves 1 and 2. One notable change in the variance explained by the waves is in EX03, where wave 1 is much stronger than in other experiments and wave 2 is weaker--an effect that was also noted for the temperature field at $\sigma = 0.9$.

At latitude 31.5^{0}N, EX02 shows some large differences from the control cases. Wave 3 has a phase of 69^0 compared with about 38^0 in all other experiments. Wave 2 explains more than 20 per cent more variance from the zonal mean than in the other experiments, and wave 1 is much weaker than in the other experiments. Wave 1 also shifted from a phase of about 250^0 to about 270^0 in EX02. The other energy parks experiments are not from the control cases.

3.4 Harmonic Analysis of the North-South Component of the Wind (v) at $\sigma = 0.5$

Unfortunately, we do not have height values at $\sigma = 0.5$ readily available, but the waves in the height field can be approximated by looking at the zonal harmonic analysis of the v component of the wind at the same level. Table 3, therefore, shows the results of the analysis at 43.5^{0}N.

Two changes in the phases of the waves are noticeable. In EX02, wave 1 has its ridge at 167^0, compared with 216^0 in the control cases. In EX03, wave 3 has its first ridge at 33^0, compared with 60^0 to 64^0 in the other cases.

In the control cases, wave 4 explains most of the variance from the zonal mean (60 per cent), with wave 2 explaining the next highest amount (16 per cent). In EX01, the largest change is in wave 3, which explains 30 per cent of the variance compared with about 5 per cent, in the control cases, wave 1 also explains more variance, while waves 2 and 4 explain less. In EX02, wave 3 again demonstrates the largest change, with only small changes in the other waves. In EX03, wave 4 explains 69 per cent of the variance from the mean, with the other three waves contributing very little. Harmonic analysis of the difference fields shows that much of the variance from the zonal mean differences is in waves 3 and 4 for all three energy parks experiments.

At 58.5^{0}N, there are no large changes in the phases of waves 1 to 4. The variance explained by the waves is similar in EX01 to the average of the control cases, with wave 3

Table 3. North-south (v) component of the wind at $\sigma = 0.5$, 43.5^0N.

	Wave 1	Wave 2	Wave 3	Wave 4
Average of 3 Controls				
Amplitude ($m \cdot sec^{-1}$)	0.5	2.4	1.3	4.5
Phase (^{0})	216	174	64	49
Variance (%)	0.8	16.2	4.8	59.8
EX01				
Amplitude ($m \cdot sec^{-1}$)	2.0	3.0	4.9	5.8
Phase (^{0})	24.4	3	64	45
Variance (%)	5.3	11.9	32.0	43.6
EX02				
Amplitude ($m \cdot sec^{-1}$)	0.4	2.3	3.0	4.5
Phase (^{0})	167	167	60	45
Variance (%)	0.5	14.0	24.0	54.8
EX03				
Amplitude ($m \cdot sec^{-1}$)	0.7	2.2	2.1	6.5
Phase (^{0})	211	164	33	48
Variance (%)	0.8	8.2	7.3	69.0
EX01 Minus Average of 3 Controls				
Amplitude ($m \cdot sec^{-1}$)	1.6	1.1	3.7	2.0
Phase (^{0})	252	26	64	34
Variance (%)	11.1	5.5	60.3	18.7
EX02 Minus Average of 3 Controls				
Amplitude ($m \cdot sec^{-1}$)	0.4	0.6	1.7	1.4
Phase (^{0})	89	121	58	24
Variance (%)	2.2	3.9	38.1	24.4
EX03 Minus Average of 3 Controls				
Amplitude ($m \cdot sec^{-1}$)	0.2	0.8	2.5	2.1
Phase (^{0})	196	120	23	44
Variance (%)	0.3	4.1	42.5	29.1

explaining about half of the total. In EX02, however, the dominance of wave 3 is almost eliminated, with all four waves explaining between 15 and 27 per cent of the variance. In EX03, wave 4 explains 50 per cent of the variance while wave 3 explains only 2 per cent, a large reduction from the control case value. Harmonic analysis of the difference fields at 58.5°N shows that the largest part of the variance from the zonal mean difference is explained by wave 3 in all three energy parks experiments.

At 31.5°N, the phase of wave 2 in EX01 is different from the other experiments, otherwise there are no noticeable shifts in phase. In the control cases, wave 4 explains most of the variance from the zonal mean, and this pattern is not changed in the three energy parks experiments. In the analysis of the difference fields it is found that for EX02 and EX03 the first 4 waves together do not explain more than 20 per cent of the variance from the zonal mean of the differences, requiring that waves of small wavelength explain the variance. In EX01, wave 4 explains the largest amount (42 per cent) of the variance.

3.5 Summary of Harmonic Analysis Results

Table 4 summarizes the largest changes in the percentage of variance explained by the first four waves for the three energy parks experiments and the three latitude lines under consideration.

EX01, in which two energy parks were situated in the mid-latitudes, had no large changes in the waves in the tropical latitudes. Elsewhere effects on waves were mixed, depending on latitude and variable under consideration.

In EX02, in which the Atlantic energy park was situated in the tropical Atlantic, no large changes in waves in the temperature of the lowest layer are noted. Again, the changes elsewhere are mixed but with a tendency towards a decrease in the amplitude of wave 1 and an increase in the amplitude of wave 2.

In EX03, in which only the mid-latitude Atlantic energy park was considered, there is, as in EX01, no large change in the waves in the tropical latitudes. In the temperature field there is a strong tendency towards a larger wave 1, and in the wind field towards a larger wave 4.

In the harmonic analysis of the differences, EX01 and EX03 have large wave 3 responses in temperature and in the v component of the wind at σ level = 0.5.

Gilchrist (1975) summed up the results of EX01 by pointing out that the model had responded to the heat input by producing a large wave 3 response. This can be seen in Table 1, in the

Table 4. Summary of the large changes in variance explained by the first four waves in the three energy parks experiments at the three latitudes under consideration.

Temperature $\sigma = 0.9$

	EX01	EX02	EX03
58.5	Wave 1 decreased Wave 2 increased	No change	Wave 1 much increased Waves 2 & 3 decreased
43.5	No large change	No large change	Wave 1 slightly increased Wave 2 slightly decreased Waves 3 & 4 small increase
31.5	No large change	No large change	No large change

Temperature $\sigma = 0.5$

	EX01	EX02	EX03
58.5	No large change	No large change	Wave 1 increased Wave 2 decreased
43.5	Wave 1 increased Wave 2 decreased Wave 3 increased	Wave 1 decreased Waves 2 & 3 increased	Waves 3 & 4 increased Waves 1 & 2 decreased
31.5	No large change	Wave 1 much decreased Wave 2 increased	No large change

(v) at $\sigma = 0.5$

	EX01	EX02	EX03
58.5	Waves 1 & 2 decreased Waves 3 & 4 increased	Wave 3 decreased Wave 4 increased	Wave 2 decreased Wave 3 much decreased Wave 4 much increased
43.5	Waves 1 & 3 increased Wave 2 decreased	Wave 1 decreased	Waves 3 & 4 increased
31.5	No large change	No large change	No large change

analysis of the difference in temperature of the lowest model layer between EX01 and the average of the controls. However, we see in the same Table that EX02 produced an even larger wave 3 response, while EX03 produced a wave 3 and a wave 1 response. Since only one energy park was inserted in EX03 we would expect a response in wave 1.

It is notable that the response in the waves was different in the three cases, which again points to the fact that the model is sensitive to the amount and location of the heat input. The results also show that the effect of the heat input is not only felt in the surface layers of the model, but has had an impact in the upper layers also.

4. CONCLUSIONS

Two previous experiments with the UKMO atmospheric circulation model, which investigated the response of the simulated northern hemisphere circulation to ocean energy parks, showed that the circulation was changed in the vicinity of the parks and elsewhere in the hemisphere. The combination of two extra-tropical energy parks had more impact than a combination involving one park in tropical latitudes.

A further experiment, in which there is one energy park with a total heat output of 1.5 x 10^{14} W in the mid-latitude Atlantic, produces effects of the same order of magnitude as in the first experiments, as far as changes in surface pressure, temperature in the lowest model layer, and precipitation are concerned. There are some qualitative similarities in response between the new experiment and the first of the previous experiments.

Analysis of the results of the first three experiments made so far suggest that (1) results from further experiments will be useful in interpreting the model's response to large inputs of waste heat; (2) further analysis of the first three experiments in terms of variables from higher levels of the atmosphere should be made; and (3) a better estimate of the model's inherent variability is required so that the significance of the model's response to the heat input can be more properly assessed.

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