THE IMPACT OF WASTE HEAT RELEASE ON CLIMATE: EXPERIMENTS WITH A GENERAL CIRCULATION MODEL

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RR-80-21
April 1980

Reprinted from *Journal of Applied Meteorology*, volume 18 (1979)

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
Laxenburg, Austria

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FOREWORD

The Energy Systems Program at the International Institute for Applied Systems Analysis has, through one of its subtasks, studied possible climatic constraints on the implementation of global energy systems. One important aspect of this problem of constraints is the impact of waste heat on climate.

To shed light on this aspect, this paper reports the findings of a series of experiments performed with a global circulation model. The underlying scenario assumes the extreme case where the world's waste heat is released at only one or two remote points in the ocean.

This research was supported by the United Nations Environment Programme (UNEP) and was carried out in collaboration with the Meteorological Office, Bracknell, United Kingdom, and the Kernforschungszentrum, Karlsruhe, Federal Republic of Germany.

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Reprinted from JOURNAL OF APPLIED METEOROLOGY, Vol. 18, No. 12, December 1979
American Meteorological Society
Printed in U. S. A.

The Impact of Waste Heat Release on Climate: Experiments with a General Circulation Model

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(Manuscript received 7 November 1978, in final form 27 March 1979)

ABSTRACT

Experiments were made with the Meteorological Office general circulation model (GCM) to investigate the response of the simulated atmospheric circulation to the addition of large amounts of waste heat in localized areas. The concept of large-scale energy parks determined the scenarios selected for the five perturbation experiments. Waste heat totaling 150 or 300 TW was added to the sensible heat exchange between the surface and air at energy parks in the Atlantic and Pacific Oceans in four experiments. In a fifth experiment, 300 TW were added to a 10 m deep "ocean box" simulated beneath the energy parks. Forty-day averages of meteorological fields from the five waste heat experiments and from three control cases are compared. Model variability is estimated on the basis of the three control cases. The regional and hemispheric responses of the atmospheric circulation are discussed, with emphasis on the magnitude of the heating rates and 500 mb height changes. The main conclusions that can be drawn are that the model exhibits a nonlinear response to the waste heat input and that, in middle latitudes, the spatial scale of the response is large even though the heat input scale is small.

1. Introduction

The Energy Systems Program of the International Institute for Applied Systems Analysis (IIASA) is studying global aspects of energy systems in terms of resources, demands, strategies and constraints. One constraint on any energy system is its possible impact on climate.

World primary energy consumption in 1975 was about 8 terrawatt-years per year or 8 TW (1 TW $= 10^{12}$ W). Growth in energy demand is stimulated by many factors, predominant among which are the world population growth, the development of less-developed countries and continued industrialization in developed countries. Detailed analysis of such factors suggests that the energy demand 50 years from now will be in the region of 25–40 TW (IIASA Energy Systems Program, 1979).

The present paper considers the possible impact of large amounts of waste heat release (from the large-scale deployment of energy conversion systems) on climate. The study was made possible through an agreement reached between the Meteorological Office (Bracknell, U.K.) and IIASA to use the Meteorological Office general circulation model (GCM) in a series of experiments to investigate the impact of waste heat on the simulated atmospheric circulation.

The impact of waste heat on simulated atmospheric circulation has previously been studied by Washington (1971, 1972) and Llewellyn and Washington (1977). Washington (1971) investigated the response of the National Center for Atmospheric Research (NCAR) GCM to the addition of 24 W m^{-2} over all continental and ice regions. There was, on the average, a 1–2 K increase in surface temperature with an 8 K increase over Siberia and northern Canada.

Washington (1972) considered a per capita energy usage of 15 kW, a population of 20 billion, and a heat input distributed according to present-day population density. It was concluded, however, that the thermal pollution effects were no greater than the inherent noise level of the model.

Llewellyn and Washington (1977) discussed a

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0021-8952/79/121501-11$06.75

further experiment with the NCAR GCM, in which heat was added to an area extending from the Atlantic seaboard of the United States to the Great Lakes and Florida. It was assumed that the energy consumption was equal to that presently consumed in Manhattan Island, i.e., 90 W m^{-2}. Other regions of the globe were not modified. Temperature differences of as much as 12 K were observed in the vicinity of the anomalous heating, but the heating had little effect above the surface layer.

Washington and Chervin (1979), using an improved version of the NCAR GCM, considered the same heat input as Llewellyn and Washington in both January and July experiments. A surface temperature change of 12 K over the area of heat input was found in the January experiment. Smaller but still significant changes, with a maximum of 3 K, were found in the July experiment. Significant changes in precipitation and soil moisture were also found in the prescribed change region. However, neither experiment produced any evidence of a coherent, statistically significant, downstream response over the Atlantic Ocean or Europe.

Other studies of the impact of heat sources on the atmospheric circulation include the use of linearized models to study the effects of heat forcing (e.g., Smagorinsky, 1953; Döös, 1962; Saltzman, 1965; Egger, 1977) and the use of GCM's to study the impact of sea-surface temperature anomalies (SSTA's) (e.g., Rowntree, 1972, 1976; Chervin *et al.*, 1976; Kutzbach *et al.*, 1977).

The experiments with the Meteorological Office GCM described in this paper investigated the response of the simulated atmospheric circulation to the addition of large amounts of heat in localized ocean areas. In three experiments a heat input of 300 TW was used, while in two experiments 150 TW were added. The input of 300 TW was chosen for the first experiment since the earlier experiments of Washington (1972) had also considered this amount and a basis for comparison was therefore available. It was also recognized, on the basis of the results of earlier GCM experiments, that the input of unrealistically large anomalies appeared to be necessary in order to ascertain a significant model response.

Section 2 of the paper describes the model and the scenarios for the five prescribed change experiments. In Section 3 we discuss the regional and hemispheric responses of the atmospheric circulation, with reference to 500 mb height changes.

2. The experiments

a. The model

The Meteorological Office general circulation model has been described by Corby *et al.* (1972). It has five levels in the vertical, equally spaced in terms of the vertical coordinate σ [pressure (p)/surface pressure (p_*)]. The horizontal resolution is 3° in the latitudinal direction and the spacing of the grid points along lines of latitude gives approximately the same resolution in the longitudinal direction. The version of the model used in this study includes only the Northern Hemisphere. Prescribed conditions include the earth's orography, the solar heating rates, sea surface temperature and ice cover. The temperatures of the land surface are computed from a surface heat balance equation, assuming a heat capacity for the land. A simplified hydrological cycle is considered, in which condensation is assumed to occur when the relative humidity of the air exceeds 100%. The effects of small-scale convective motions are parameterized.

Each experiment was run for 80 simulated days with prescribed conditions maintained at their January climatological values. The results for the last 40 days were used for analysis. Three control integrations were available in the Meteorological Office for estimating the model's January climatology and its inherent variability. The control integrations are described in more detail by Rowntree (1976), who designates them C3, C4 and C6.

b. Scenarios of the experiments

The GCM experiments were designed to study the impact of ocean energy parks on simulated climate. The concept of large-scale energy parks determined the scenarios selected. As illustrated in Fig. 1, three parks, each distinguished by a letter, have been used. The heat inputs and combination of parks in the five GCM experiments are listed in Table 1.

The energy parks cannot be simulated realistically because the area involved is too small to be properly represented within the grid structure of the model. Also, a realistic scenario would include the spread of heat by ocean currents and, therefore, require a linked atmosphere-ocean model. It would also include consideration of the waste heat release at the points of use of the energy carrier (e.g., electricity) which is being produced at the energy parks. The area of each park was made equal to that of four grid boxes (i.e., 4.4×10^5 km^2), this being the smallest area that seemed likely to produce acceptable results. This representation is an approximation which, it was hoped, would retain the essential features of the meteorological problem.

In experiments EX01–EX04, the waste heat was inserted directly into the atmosphere in sensible heat form by adding 375 W m^{-2} (187.5 W m^{-2} in EX04) to the sensible heat exchange between the air and the earth's surface at the four grid points. In EX05, an "ocean box" of 10 m depth was considered below the two energy parks; the surface temperature, constant in EX01–EX04 and the control cases, was computed from the same energy balance

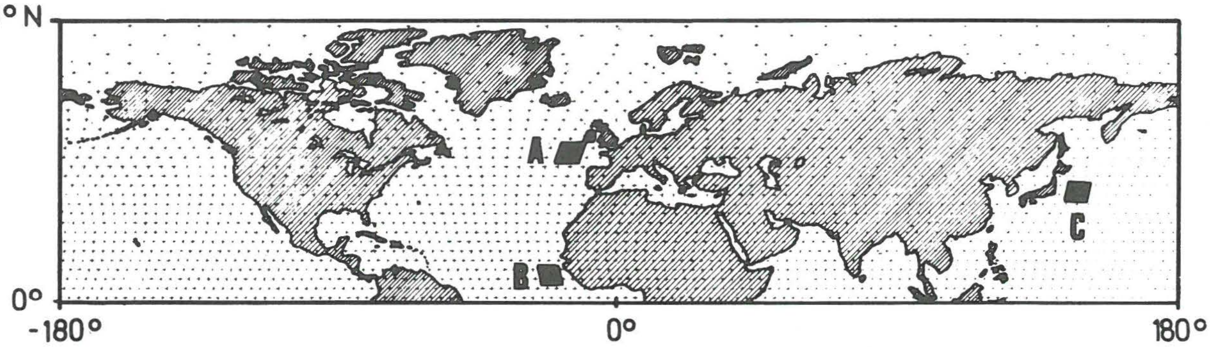

FIG. 1. Location of the three energy parks, designating each park by a letter: A: 49.5°N, 12.0–16.5°W; 46.5°N, 14.0–18.5°W. B: 10.5°N, 21.0–24.0°W; 7.5°N, 20.5–23.5°W. C: 37.5°N, 146.0–150.0°E; 34.5°N, 145.5–149.5°E.

formulation as for land points, but assuming an effective heat capacity of 4.18×10^7 J m^{-2} K^{-1}. In EX05, therefore, the added heat was released to the atmosphere in both sensible and latent forms.

3. Results of the experiments

a. Estimation of inherent variability of the model

An important aspect of the analysis of the results of GCM prescribed change (sensitivity) experiments is to determine how much of the difference from control integrations is due to the prescribed change and how much is a result of the model's inherent variability. Chervin *et al.* (1976) used a significance test based on Student's *t*-statistic and the same method has been used in this study. Recognizing problems in the purely statistical approach, however, emphasis has been placed here on studying the similarities among experiments that have common features. That is, the results of successive experiments after the first have been examined with an *a priori* expectation that certain responses which are physically realistic will be found. The evidence of consistent responses in accordance with the *a priori* expectation is strong evidence of their physical reality and lessens the need for dependence on a purely statistical analysis.

The inherent variability of the Meteorological Office GCM was estimated by computing the standard deviations of 40-day means, S_{40}, from the three control cases that were available. The statistical significance of the results may then be judged from

$$r = \frac{|\Delta|}{S_{40}},$$

where Δ is the difference at a grid point between the 40-day mean of a meteorological variable in a prescribed change experiment and the average of the three control experiments. The ratio r has a Student's t-distribution. Values of $r > 5.0$ are statistically significant at the 5% level. That is, if $r > 5.0$ at an individual grid point, there is a 95% chance that the difference is significant and caused by the prescribed change.

b. Sensible and latent heating at energy parks

Fig. 2 shows the sensible heat input to the atmosphere at the midlatitude Atlantic park (park A in Fig. 1) and at surrounding points in each of the energy park experiments. No waste heat was added at this park in EX02. In EX01, EX03 and EX04, the total heat input differs only slightly from the amount of waste heat; the heat was inserted in an area where the atmosphere is normally stable and, therefore, where heat exchange values are small in the control integrations. By contrast, in EX05, the sensible heat input is less than half of the waste heat input. However, as shown in Table 2, the latent heat flux from the surface is greater in EX05 than in the other experiments at park A. In addition, a marked increase of precipitation directly over the energy parks in EX05 implied the release of the latent heat of condensation of an additional average 83 W m^{-2}

TABLE 1. The combination of energy parks and heat input in five GCM sensitivity experiments.

Experiment	Energy parks	Heat input	Remarks
01	A & C	1.5×10^{14} W at each park	Total heat input 3×10^{14} W
02	B & C	1.5×10^{14} W at each park	Total heat input 3×10^{14} W
03	A only	1.5×10^{14} W	Total heat input 1.5×10^{14} W
04	A & C	0.75×10^{14} W at each park	Total heat input 1.5×10^{14} W
05	A & C	1.5×10^{14} W at each park	Heat added to "ocean box" below each park rather than directly to atmosphere

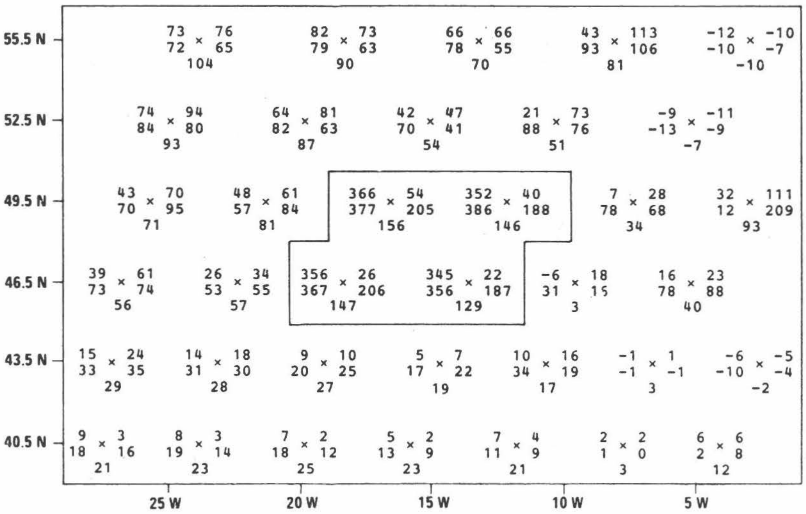

FIG. 2. Sensible heat values (W m^{-2}) in the vicinity of the midlatitude Atlantic energy park (park A), averages for days 41–80. Values in the top line at each grid point are for EX01 (left) and EX02 (right). Values in second line at each grid point are for EX03 (left) and EX04 (right). Values below are for EX05.

of sensible heat at park A (as compared with the control cases). In EX01–EX04, there is no large increase in precipitation over park A and thus no additional sensible heat input. Consideration of the difference in sensible heat input from the average of the control integrations in the vicinity of park A shows that local changes in the meteorological variables have tended to offset the waste heat input by reducing the sensible heat exchanged at the surface, but the magnitude of this effect is not more than about 15%.

The total sensible heat flux for the Pacific energy park (C) is given in Fig. 3. The total input is greater than the waste heat input in most cases, due to a positive contribution from surface exchanges at the park. In the vicinity of the park there are large sensible heat fluxes due to the cold air flowing off the Asian continent over the relatively warm ocean. In EX01, the total heat input is larger than the waste heat input at all four grid points, while in EX02 it is less. In EX04, the sensible heat input is greater than the waste heat input, but not by as large a margin as in EX01. In EX05, the total sensible heat input varied substantially among the grid points, but on the average it is about the same as in EX04; i.e., less than half of the waste heat input. As for park A, however, the latent heat flux in EX05 from the surface is also increased at park C, and a precipitation increase directly over the energy park adds a further 26–133 W m^{-2} (averaging 81 W m^{-2}) to the atmosphere.

TABLE 2. Differences in latent heat flux at energy parks (W m^{-2}) using 40-day means averaged for four grid points of each energy park.

Experiment	Park A	Park B	Park C
Average of controls (C)	116	160	170
EX01 − C	−62	−5	+136
EX02 − C	+3	−90	−48
EX03 − C	−25	−11	−21
EX04 − C	−9	+1	−3
EX05 − C	+235	+2	+240

Table 2 shows the differences between the latent heat flux in the energy parks experiments and the average of the control cases averaged for each energy park. In EX05, the latent heat flux at parks A and C increased by ~240 W m^{-2}. That is, during days 41–80 of EX05, 375 W m^{-2} were added to the ocean box beneath each energy park, the latent heat flux at the surface was about 351 W m^{-2} (park A) and 411 W m^{-2} (park C), while the sensible heat flux was about 145 W m^{-2} (park A) and 210 W m^{-2} (park C). Over both parks (and generally not over the surrounding grid points), however, the precipitation increased and thus much of the latent heat was converted directly to sensible heat input to the atmosphere. At both parks A and C the average sensible heat release due to condensation over the energy park was 171 W m^{-2} (40-day mean).

Table 2 shows a major difference between the response of EX01 and that of EX02 and EX04 at the Pacific energy park. In EX01, in addition to the enhancement of the sensible heat flux at park C, there was an enhancement of the latent heat flux which did not occur at any of the other energy parks in the experiments without an ocean box. Such an enhancement can be attributed to the atmospheric circulation established over the area, as is illustrated

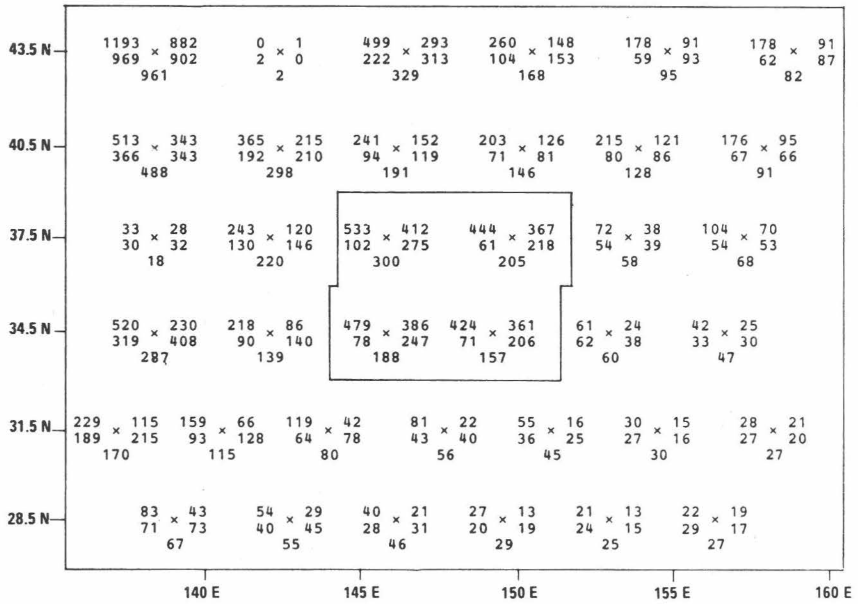

FIG. 3. As in Fig. 2 except for midlatitude Pacific energy park (park C).

for park C in EX05 in the next section. Unlike EX05, however, the latent heat flux at park C in EX01 was not converted immediately to sensible heat by condensation; the precipitation increase was downstream where the sensible heat input was ~50 W m^{-2} greater than in the control cases, as a result of increased precipitation. This heat input possibly contributed to maintaining the sea level pressure decrease downstream of park C.

c. Surface temperature changes at energy parks in EX05

As described in Section 2, in EX05, 375 W m^{-2} were added to an ocean box at the four grid points of the two energy parks (A and C). Fig. 4 shows the surface temperature, latent heat and sensible heat fluxes in EX05 for the average of the four grid points at each park for each of days 41–80.

At park A, the sea-surface temperature is ~4 K higher than in the control cases and the sensible and latent heat fluxes from the surface increased. The largest variations from the mean values of these variables occur between days 58 and 66. Examination of the u and v components of the wind shows that the cooling of the sea surface temperature between days 58 and 66 and the associated increase in sensible and latent heat flux from the surface occurred when the surface wind flow became northerly, in contrast to the southerly flow before this period.

At park C, the fluctuations around the means are much larger. The sea surface temperature again is increased ~4 K compared with the control cases. The large increases in the sensible and latent heat fluxes from the surface and consequent lowering of the sea surface temperature between days 60 and 70 are a result of a change of the surface wind flow from easterly (off the Pacific) before the period to westerly (off the continent).

At both energy parks, therefore, the sea surface temperature in EX05 increased by ~4 K on the average. Fig. 4 shows that there were no apparent long-term trends in the sea surface temperature, but that the temperature fluctuated depending on the direction of flow of the surface wind. Thus, when the SST at park C was ~7 K higher than the average in the control cases (day 62), an atmospheric circulation pattern was established which caused it to cool down to the control case mean value.

d. Longitudinal differences in sea level pressure and 500 mb height

Figs. 5 and 6 show the longitudinal distributions of differences in sea level pressure and 500 mb height between the control cases and the energy parks experiments. The differences are averaged for two lines of latitude in each figure.

For the lines of latitude which pass through park A (Fig. 5), it is seen that there is a fairly consistent response to the heat input at park A in all of the experiments. In the Atlantic-European sector, in EX01, EX03, EX04 and EX05, there is a relative ridge in the 500 mb height and sea level pressure at 30–50°W and a relative trough at 10–30°E. These features can also be seen further south (Fig. 6) for EX01, EX03 and EX05. Mostly there is evidence of a westward shift with height of the relative ridge and trough.

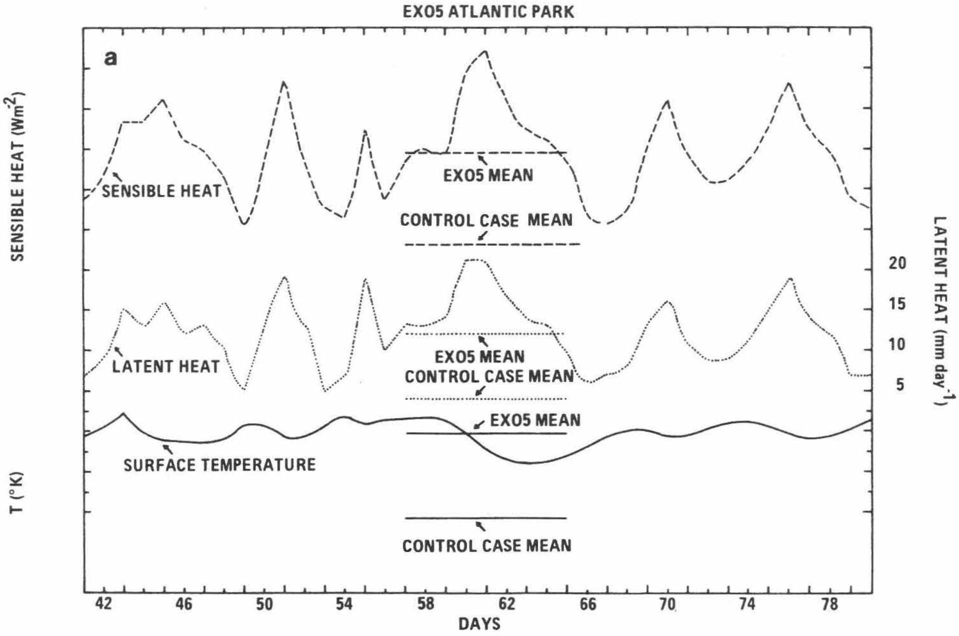

FIG. 4a. Sea surface temperature (K), latent heat flux (W m^{-2}) and sensible heat flux (W m^{-2}) for the average of the four grid points in park A for each of days 41–80 in EX05. 40-day mean values for EX05 and the average of the control cases are also shown.

Fig. 5 shows also that, in the vicinity of park A, the response in EX01 and EX03 (where the heat input was 375 W m^{-2}) was greater than in EX04 (heat input of 187.5 W m^{-2}). Moreover, the response in the experiments with the larger heat input extends further to the north and south. These points tend to confirm that the relative trough and ridge are a significant response and not merely random variations

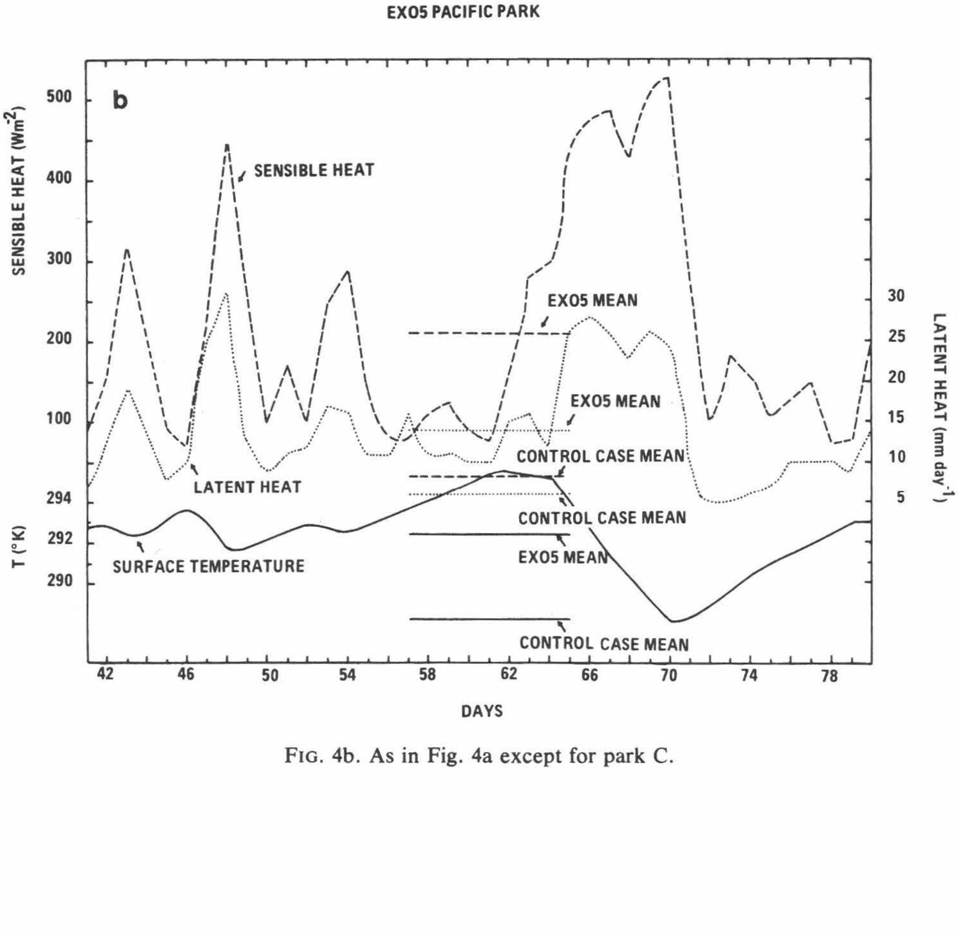

FIG. 4b. As in Fig. 4a except for park C.

of the model. The results of EX05 are unexpected, however, in that, although the sensible heat input is much less than in EX01, the amplitude of the ridge over park A is greater. However, the enhanced evaporation at park A in EX05 (Table 2) leads to a total heat input greater than in EX01. Also, as discussed above, the increased precipitation at the park is equivalent to an additional average of about 80 W m^{-2}. EX05 is closer to being a conventional SSTA experiment than the other energy park experiments, yet the response is much larger than might be expected from the results of Rowntree (1976) and Kutzbach *et al.* (1977), for example. However, the anomaly in EX05 is in the eastern midlatitude Atlantic and the impact of SSTA's in these locations have not been investigated. A possible explanation for the unexpectedly large response is that anomalies in the eastern Atlantic, where the normal variance

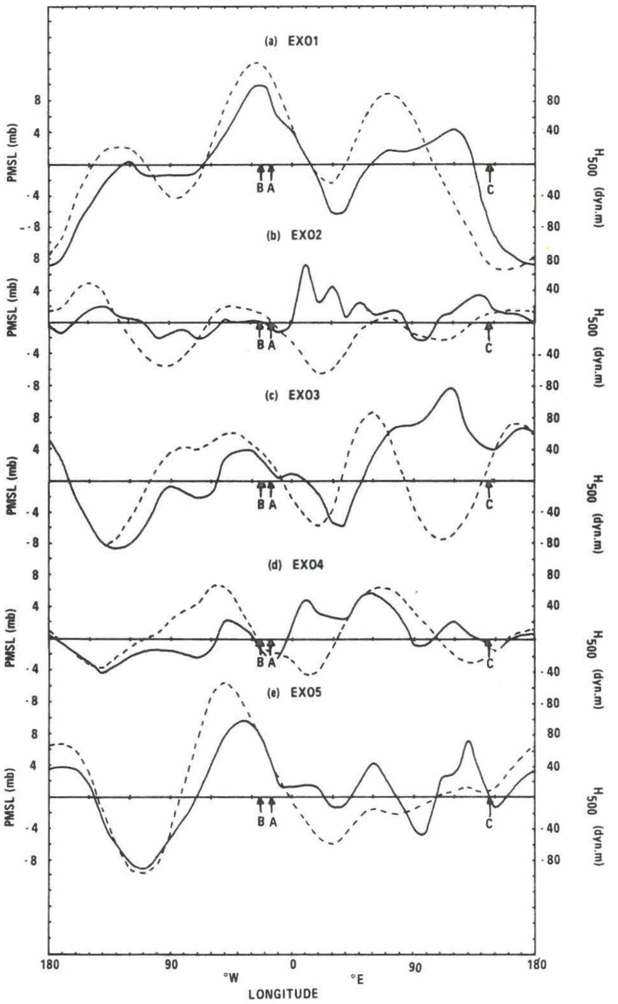

FIG. 5. Longitudinal distribution of differences in sea level pressure (solid) and the height of the 500 mb surface (dashed) between the energy parks experiments and the average of the control cases. Values are averages of days 41–80 and for 49.5 and 46.5°N.

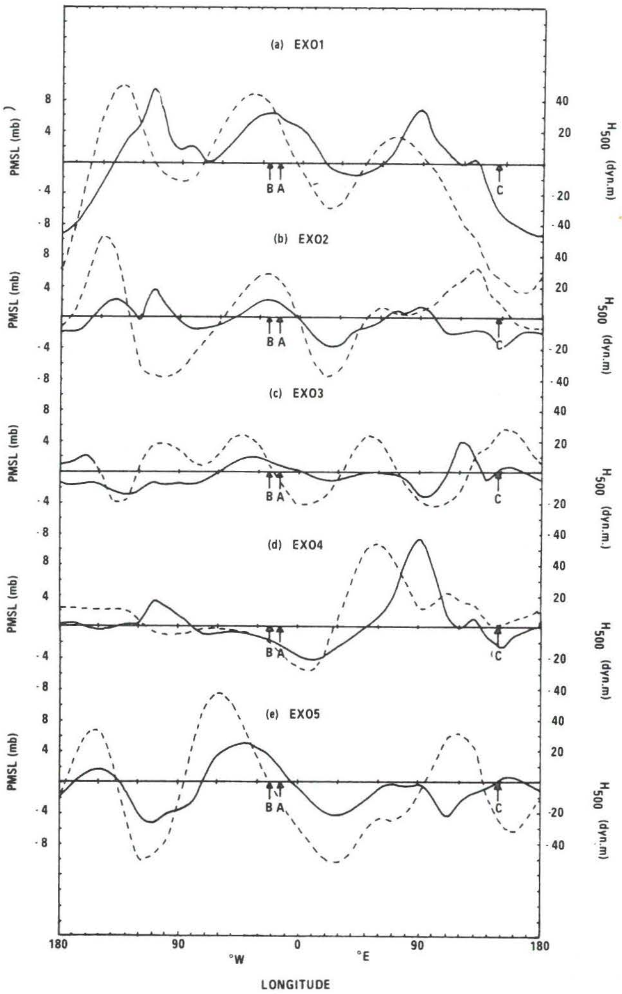

FIG. 6. As in Fig. 5 except averages of 37.5 and 34.5°N.

of surface temperature is low, have a relatively large impact, perhaps because the depression tracks are altered most readily by changes some distance downstream from the main developmental region.

In contrast, it is difficult to discern a consistent response to the heat input at park C. As already noted, the circumstances at this park are very different from those at park A. Waste heat is inserted where the heat input is naturally very large and very variable. At the latitude of the park (Fig. 6) there is a tendency for downstream ridging between 180 and 120°W in EX01, EX02 and EX05, but this response is limited in horizontal extent and does not occur at higher latitudes. The largest response to the heat input in park C occurs in EX01, where a large relative trough occurs over and downstream of the heat input.

e. Changes in the distribution of 500 mb height

Fig. 7 shows the geographical distribution of the differences in 40-day mean 500 mb height between

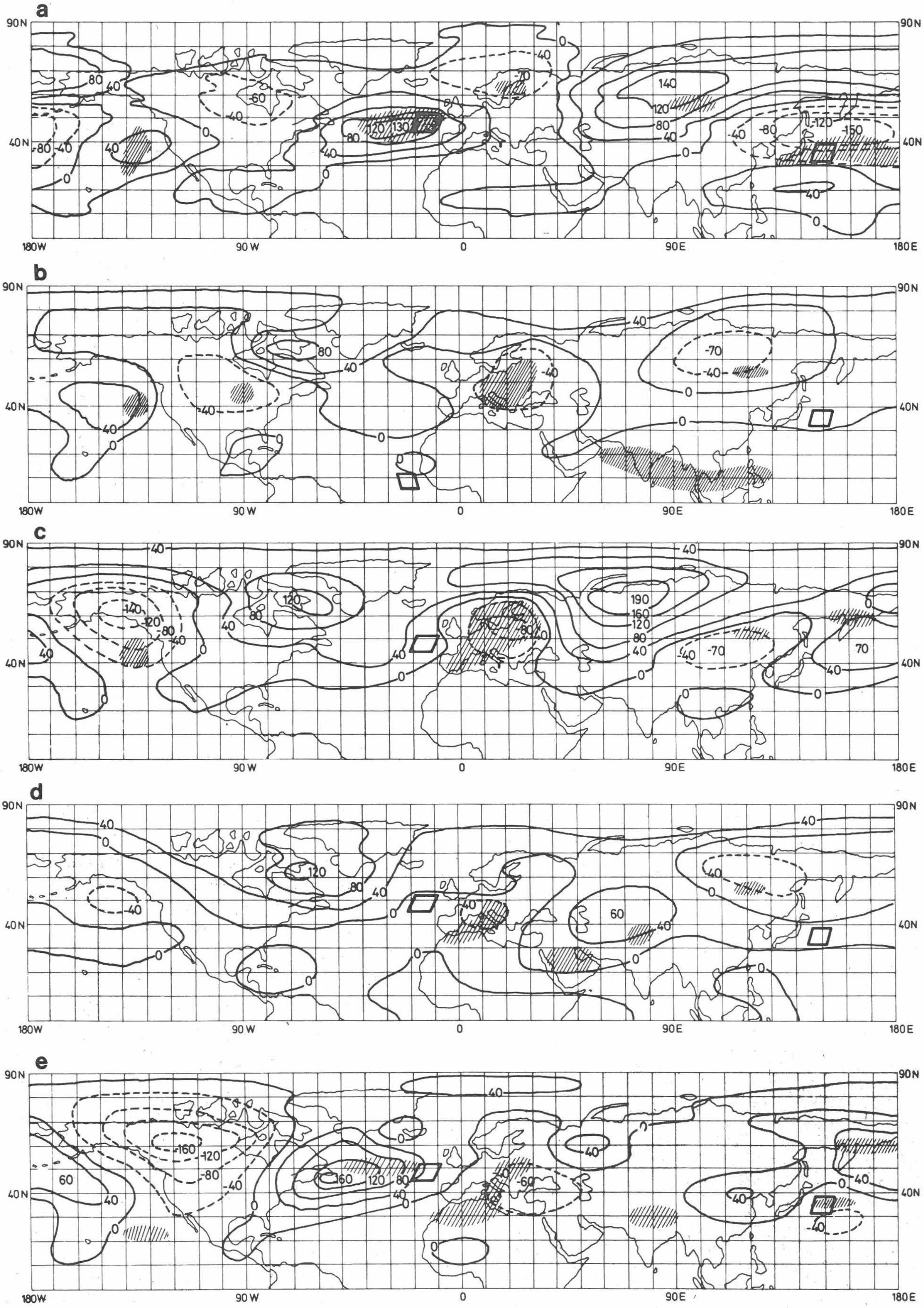
a
90N
40N
180W
90W
0
90E
180E
b
c
d
e

TABLE 3. Amplitude (dyn m) and phase (longitude of first ridge east of Greenwich) and total percent variance explained for waves 1–4. Computed for difference in height of 500 mb surface between the energy parks experiments and the average of the control cases. Harmonic analysis was performed on 40-day mean differences for three latitude lines (58.5°N, 43.5°N, 31.5°N).

	Wave 1		Wave 2		Wave 3		Wave 4		Percent total variance
					Latitude 58.5°N				
EX01 − CON*	50	105°	14	90°	38	82°	14	75°	97
EX02 − CON	21	258°	13	163°	33	64°	6	83°	77
EX03 − CON	40	24°	57	107°	65	56°	35	72°	96
EX04 − CON	44	304°	18	114°	23	52°	15	4°	93
EX05 − CON	40	49°	59	158°	62	63°	11	32°	98
					Latitude 43.5°N				
EX01 − CON	77	343°	29	73°	62	93°	21	58°	98
EX02 − CON	22	172°	15	161°	30	88°	15	48°	92
EX03 − CON	7	320°	16	160°	41	54°	28	66°	95
EX04 − CON	13	111°	22	85°	24	64°	9	66°	94
EX05 − CON	23	265°	48	141°	45	77°	21	28°	98
					Latitude 31.5°N				
EX01 − CON	13	274°	17	71°	16	88°	12	43°	91
EX02 − CON	0	234°	3	174°	12	89°	9	41°	54
EX03 − CON	5	205°	5	79°	6	47°	6	51°	59
EX04 − CON	5	52°	15	57°	9	64°	7	49°	87
EX05 − CON	13	235°	17	106°	17	79°	41	24°	88

* CON represents the average of the control cases.

the energy parks experiments and the average of the three control cases. Areas where the "signal-to-noise" ratio > 5.0 are shaded. Harmonic analysis of the differences in 500 mb height has been made for three latitude lines. The results of the analysis are given in Table 3.

In EX01 (Fig. 7a) several larger areas of 500 mb height change are found. The increase over and upstream of park A and the decrease over and downstream of park C are on a much larger spatial scale than the area of an energy park. There are essentially three major relative ridges and troughs. Some of these features have maximum intensity at ~45°N and others at ~60°N. In the harmonic analysis this shows up as a wave 3 response, whose phase does not change much with latitude, and a wave 1 response which, although accounting for the largest percentage of the variance from the zonal mean, has a different phase at each latitude.

The changes in 500 mb height in EX02, which considered heat input at parks B and C, are neither as large nor as coherent in middle and high latitudes as in EX01. The heat input made at one tropical location produced a limited response in the immediate vicinity. Downstream from park C there is an area of increased 500 mb height at 130–140°W, which is extensive and which, since it appears in all the experiments with the Pacific energy park (but not in EX03, which did not consider this park), may be a real model response. The harmonic analysis at all three latitudes shows that wave 3 explains much of the variance from the zonal means in EX02.

In EX03 (Fig. 7c), which considered only park A, the pattern of 500 mb height change in the vicinity of park A is the same as in EX01, with a height increase over and upstream of the park and a height decrease downstream. Further downstream the two experiments differ since EX03 has no Pacific energy park. Again, in midlatitudes (43.5°N), the harmonic analysis shows that the differences contain a large wave 3 component.

The differences of 500 mb height in EX04 (Fig. 7d) do not reproduce the geographical distribution of EX01, which considered the same energy parks but had twice as much heat input. The differences downstream from the Atlantic park are similar to those in EX03, though weaker. Over the Pacific there are only small changes in the 500 mb height field in EX04, which are unlike those found in the other experiments which considered the Pacific energy park. In high latitudes the differences in EX04 exhibit a large wave 1 response, while in middle

FIG. 7. Geographical distribution of the differences in 40-day mean 500 mb height (dyn m) between energy parks experiments and the average of the three control cases. Shaded areas show where the signal-to-noise ratio r is greater than 5.0 based on an estimate of model variability using 40-day means. (a) EX01, (b) EX02, (c) EX03, (d) EX04, (e) EX05.

latitudes waves 2 and 3 explain much of the variance from the zonal mean.

In EX05 the changes in 500 mb height in the vicinity of the Atlantic heat input are similar to those in EX01, with an increase over and upstream of the park and a decrease downstream. Elsewhere the similarities in response of the two experiments are not too strong. There is a large wave 3 response with the same phase at the three latitudes investigated. However, the differences in magnitudes of the large-scale features lead to substantial contributions also in wave 2 (43.5 and 58.5°N) and wave 4 (31.5°N).

With regard to the distribution of signal-to-noise ratio in the maps in Fig. 7, for each of the experiments there are areas where the ratio is large enough to suggest that the results differ significantly from the control case ensemble. However, since the number of control cases is small and only one case for each energy park scenario was considered, the ratio cannot be used as a definitive test of significance. As pointed out at the beginning of Section 3, the aim of successive experiments has been to check particular consistent, physically realistic responses in the experiments rather than rely on statistical tests of significance.

Nevertheless, for both EX01 and EX05, the signal-to-noise ratio is greater than 5 in the area of height increase over and upstream of park A and the area of height decrease downstream of park A. In both EX03 and EX04, which also considered park A, the ratio is greater than 5 in the region of 500 mb height decrease downstream from the park. Thus, there appears to be statistical evidence to support the view that park A produces a genuine (and similar in each experiment) response in the model.

4. Conclusions

The response of the simulated atmospheric circulation to the insertion of large amounts of waste heat at ocean energy parks has been investigated using five prescribed change experiments and three control cases of the Meteorological Office GCM.

Four experiments that included an energy park in the midlatitude eastern Atlantic gave qualitatively similar results in the region surrounding the park. In each case, the flow at middle levels of the atmosphere became more anticyclonic upstream and cyclonic downstream from the park. The amount by which the flow was changed and the latitudinal extent of the significant effect depended on the heat input, and for the smaller heat input used (0.75×10^{14} W) was small. The longitudinal extent between the positions of relative ridging and troughing was ~60–80°, though this apparently depended in some measure on developments elsewhere in the hemisphere. Statistical evidence supports the view that the park produces a consistent response in the model.

One experiment included an energy park in the Atlantic off West Africa. In this case the atmospheric effects were mainly in the immediate vicinity of the park, with the heat input creating greatly enhanced rainfall.

The third location for an energy park was off the east coast of Japan, in the region of a pronounced climatological upper trough. In this instance, the various experiments showed considerable variation in response. In the first experiment, the effect of the energy park was to deepen the climatological trough and so, in combination with the eastern Atlantic changes, produce a large response in waves 1 and 3.

It is of interest to compare qualitatively the results of the energy parks experiments with those of GCM experiments to investigate the effects of sea surface temperature anomalies. In the latter it has been found that, with anomalies of large horizontal extent in the tropics, significant atmospheric effects extend beyond the region of the anomalies themselves (e.g., Rowntree, 1972, 1976). When the anomalies are in middle latitudes, it is difficult to detect significant changes away from the anomalies (e.g., Kutzbach *et al.*, 1977; Chervin *et al.*, 1976). In the present experiments, this response is apparently reversed: when the heat is added as sensible heat to the atmosphere at small concentrated sources, the response of the atmosphere is greater when the heat input is in middle latitudes than when one of the point sources is in tropical latitudes. In the fifth experiment the waste heat was added to 10 m deep ocean boxes simulated at two middle latitude energy parks. When equilibrium was reached, the ocean temperature at the four grid points of each energy park was ~4 K higher than in the control cases and the sensible and latent heat fluxes increased. EX05 is closer to being a conventional SSTA experiment than the other energy parks experiments, yet the response is much larger than might be expected from the results of those with SSTA's in midlatitudes. However, as pointed out earlier, the largest response in EX05 is over the Atlantic, where the heat input was made in the eastern midlatitude Atlantic Ocean and the impact of SSTA's in these locations has not been investigated. The large response here could be because the normal variance of surface temperature in the eastern Atlantic is low and the input of large anomalies particularly influences the depression tracks.

Overall, the energy parks experiments indicate that there is a possibility that the input of large amounts of heat could cause large, coherent changes in the atmosphere, not just over the areas of heat input but also elsewhere in the hemisphere. The response may vary according to the location, amount and manner of heat input.

Acknowledgments. The Energy and Climate Subtask at IIASA is supported by the United Nations Environment Programme. EX01 and the three control cases described in this paper were run on the computer of the Meteorological Office, Bracknell, U.K. EX02, EX03, EX04 and EX05 were run on the computer of the Kernforschungszentrum, Karlsruhe, F.R.G. The assistance of J. Walker (Meteorological Office) and R. Kuhn (Kernforschungszentrum) in supervising and running of the model is gratefully acknowledged. We would also like to acknowledge the contributions of Drs. A. Murphy and P. Rowntree to the study. The comments of R. M. Chervin, W. M. Washington and K. Fraedrich on a draft of the paper are appreciated.

REFERENCES

Chervin, R. M., W. M. Washington and S. H. Schneider, 1976: Testing the statistical significance of the response of the NCAR general circulation model to North Pacific Ocean surface temperature anomalies. *J. Atmos. Sci.*, **33**, 413–423.

Corby, G. A., A. Gilchrist and R. L. Newson, 1972: A general circulation model of the atmosphere suitable for long period integrations. *Quart. J. Roy. Meteor. Soc.*, **98**, 809–832.

Döös, B. R., 1962: The influence of exchange of sensible heat with the earth's surface on the planetary flow. *Tellus*, **14**, 133–147.

Egger, J., 1977: On the linear theory of the atmospheric response to the sea-surface temperature anomalies. *J. Atmos. Sci.*, **34**, 603–614.

IIASA Energy Systems Program, 1979: *Energy in a Finite World –A Global Systems Analysis.* International Institute for Applied Systems Analysis, Laxenburg, Austria (in preparation).

Kutzbach, J. E., R. M. Chervin and D. D. Houghton, 1977: Response of the NCAR general circulation model to prescribed changes in ocean surface temperature. Part I: Midlatitude changes. *J. Atmos. Sci.*, **34**, 1200–1213.

Llewellyn, R. A., and W. M. Washington, 1977: Regional and global aspects. *Energy and Climate: Outer Limits to Growth*, Geophysics Research Committee, National Research Council, Washington, DC, 106–118.

Rowntree, P. R., 1972: The influence of tropical east Pacific Ocean temperatures on the atmosphere. *Quart. J. Roy. Meteor. Soc.*, **98**, 290–321.

——, 1976: Response of the atmosphere to a tropical Atlantic Ocean temperature anomaly. *Quart. J. Roy. Meteor. Soc.*, **102**, 607–625.

Saltzman, B., 1965: On the theory of the winter-average perturbations in the troposphere and stratosphere. *Mon. Wea. Rev.*, **93**, 195–211.

Smagorinsky, J., 1953: The dynamical influence of large-scale heat sources and sinks on the quasi-stationary mean motions of the atmosphere. *Quart. J. Roy. Meteor. Soc.*, **79**, 342–366.

Washington, W. M., 1971: On the possible uses of global atmospheric models for the study of air and thermal pollution. *Man's Impact on Climate*, W. H. Matthews *et al.*, Eds., The MIT Press, 265–276.

——, 1972: Numerical climate change experiments: The effect of man's production of thermal energy. *J. Appl. Meteor.*, **11**, 763–772.

——, and R. M. Chervin, 1979: Regional climatic effects of large-scale thermal pollution: Simulation studies with the NCAR general circulation model. *J. Appl. Meteor.*, 3–16