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IMPACT OF WASTE HEAT ON SIMULATED CLIMATE: A MEGALOPOLIS SCENARIO

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PREFACE

The IIASA Energy Systems Program studies global aspects of energy systems in terms of resources, demand, options, strategies and constraints. One constraint on any energy system is represented by its impact on climate, a topic which was investigated by the Energy and Climate Subtask.

This report is the fourth in a series of papers (Murphy et al., 1976; Williams et al., 1977a,b) describing the efforts in studying the impact of waste heat on the atmospheric circulation. The problem was studied using a numerical model of the atmospheric general circulation. Results of model experiments using 5 scenarios for waste heat input were described in the earlier reports. Here three more experiments are reported which were made with the same model but with a different scenario.

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SUMMARY

The general circulation model (GCM) of the Meteorological Office (MO), U.K., was used to investigate the impact of waste heat on simulated global climate. These experiments are a further set in a series of experiments made to investigate the behavior of the simulated circulation with different scenarios and energy releases. In contrast to the previous experiments, the heat is distributed only over continental areas, where large energy and/or population densities can be expected in the future.

The results suggest that the atmosphere responds very sensitively to the distribution of the heat input. Although the total hemispheric changes are smaller than in some of the previous experiments, there are still considerable areas where the difference between the perturbed model run and the control cases is large compared with the inherent variability of the model.

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INTRODUCTION

The Energy and Climate Subtask of IIASA's Energy Systems Program studies constraints of climate on energy systems for the medium and long-term future. One climate constraint is the impact of waste heat. Considering the concept of large energy parks, the impact on climate of five different scenarios has been investigated so far, using the atmospheric general circulation model of the Meteorological Office, United Kingdom. Results of these investigations are reported by Murphy et al. (1976) and Williams et al. (1977a,b; 1979).

The earlier experiments are designated EX01, EX02, EX03, EX04 and EX05. The scenarios considered three energy parks, which were located in the North Atlantic south west of England (Park A), in the Atlantic west of Africa (Park B) and in the North Pacific east of Japan (Park C). One or two of these islands were selected for each scenario and 75 or 150 TW were released from each of them into the model atmosphere except in EX05 where the heat was inserted into an ocean box.

These relatively unrealistic scenarios were designed as alternatives to those used in earlier model studies of the impact of waste heat (Washington 1971, 1972) where the heat was distributed over the entire continents. Washington (1971) used the NCAR general circulation model (GCM) to investigate the response of the model atmosphere to an addition of 24 Wm^{-2} over all continental and ice regions. The total amount of heat added was about one order of magnitude bigger than that used in the IIASA experiments. Results showed a 1-2^{0}C increase in surface temperature with an 8^{0}C increase over Siberia and northern Canada.

A more realistic input of energy was used by Washington (1972). A per capita energy use of 15 kW and an ultimate population of 20 billion were assumed and the thermal pollution was 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) discuss a further experiment with the NCAR GCM, in which thermal pollution was added to an area extending from the Atlantic seaboard of the U.S. to the Great Lakes and Florida. It was assumed that the energy consumption for that region was equal to that presently found in Manhattan, i.e. 90 Wm^{-2}. Other regions of the globe were not modified. Temperature differences of as much as 12°C were observed in the vicinity of the anomalous heating but the heating had little effect above the surface layer.

Washington and Chervin (1978), using an improved version of the NCAR GCM, considered the same heat input as Llewellyn and Washington (1977) in both January and July experiments. A surface temperature change of 12°C over the area of heat input was found in the January experiment. Smaller but still significant changes, with a maximum of 3°C, 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.

Following the lines of the latter series of experiments, this paper describes an investigation of a scenario in which the waste heat release areas are distributed in a more realistic way only over continental areas rather than over the oceans as in the earlier IIASA studies. This approach avoids the heat being concentrated in small energy parks and might be considered as a compromise between Washington's and IIASA's earlier experiments.

THE EXPERIMENTS

The MO General Circulation Model

The general circulation model of the Meteorological Office has been described in detail by Corby et al. (1972). The version of the model used in the present study has five levels in the vertical, equally spaced in terms of the vertical coordinate σ. The horizontal resolution is 3° in the longitudinal and latitudinal directions and only the northern hemisphere is modelled. Prescribed boundary conditions include the earth's orography, the incoming solar radiation, sea surface temperature and cloudiness. The temperatures of the land surfaces 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 the release of latent heat of condensation on the large-scale dynamics of the atmosphere are explicitly included, but the effects of small-scale convective motions are parameterized.

THE MEGALOPOLIS SCENARIO

In this scenario the heat was released from six different regions in the northern hemisphere. The selected locations represent areas where a large population and/or energy consumption density could be expected in the future (Doxiadis, 1974; National Research Council, 1977; Keyfitz, 1979; Llewellyn and Washington, 1977). As one might call this a "Megalopolis" scenario we denote the energy consumption areas M1-M6. Table 1 gives the locations of the heat input and the amount of heat released at each location for each experiment. Three experiments have been performed with this scenario and they are labeled MX01-MX03. In MX01, the same total amount of heat as in EX01, EX02 and EX05, namely 300 TW, was released from the 6 areas. In MX02 and MX03, the input was reduced to a more realistic value, i.e. 50 TW and 30 TW respectively. The latter values also compare to the brackets of primary energy consumption in 2030, as they are assumed by the IIASA Energy Systems Program (1980). Figure 1 shows the geographical distribution of the 6 areas. The size of the areas and their heat input were chosen in such a way that the heat released per square meter was the same for each grid point.

Table 1. Scenario for the Megalopolis experiments

Area	Location	Heat released MX01/MX02/MX03	Area size (km^2)
M1 (U.S.)	42°N, 81.2°W - 69.4°W 30°N, 87.1°W - 76.5°W	72/12/7.2 TW	12×10^5 km^2
M2 (EUROPE)	51°N, 4.2°E - 36.5°E 45°N, 5.7°E - 36.1°E	84/14/8.4 TW	14×10^5 km^2
M3 (U.S.S.R.)	54°N, 71.4°E - 86.2°E 48°N, 68.8°E - 82.7°E	36/6/3.6 TW	6×10^5 km^2
M4 (INDIA)	24°N, 79.5°E - 86.0°E 18°N, 78.0°E - 84.4°E	24/4/2.4 TW	4×10^5 km^2
M5 (CHINA)	36°N, 111.2°E-118.5°E 24°N, 109.4°E-116.0°E	48/8/4.8 TW	8×10^5 km^2
M6 (JAPAN)	36°N, 132.8°E-144.1°E 33°N, 133.0°E-143.9°E	36/6/3.6 TW	6×10^5 km^2
Total		300/50/30 TW	50×10^5 km^2

The experiments were performed with the GCM of the U.K. Meteorological Office. In addition to the perturbed cases, the same three control cases were used as in the previous investigations. These control experiments were run with the same version of the model and simulate unperturbed January climate. They differ from each other only as a result of small random differences in the initial conditions. The Megalopolis experiments have also been performed 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.

RESULTS

In the following, maps showing the differences in meteorological variables between the Megalopolis experiments and the average of the control cases are presented (Figure 1). The statistical significance of the results is considered by computing the ratio

$$r = \left|\frac{\Delta}{s_{40}}\right|$$

where Δ is the difference at a grid point between the perturbed case and the average of the control cases of the 40-day mean of a meteorological variable. s_{40} is the standard deviation of the 40-day mean of the same variable computed from the three control cases. Ratio r has a Student's t distribution with two degrees of freedom and values of the ratio greater than 5.0 are statistically significant at the 0.05 level (two-sided test). That is, if the ratio r for the variable under consideration is greater than 5.0 in an area, there is a 95% chance that the difference Δ is due to a response to the prescribed change and not to the inherent variability of the model. The shaded areas in Figures 2 to 4 indicate such regions where the ratio is greater than 5.0.

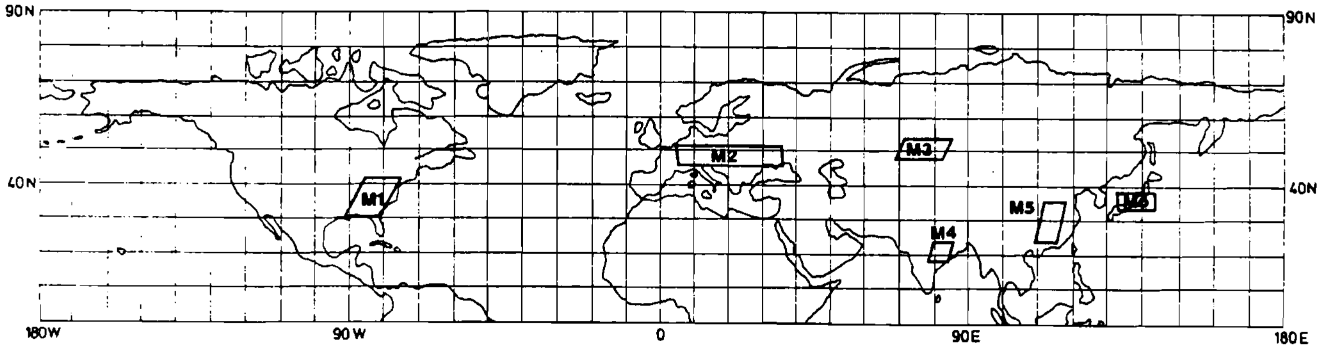

Figure 1. Locations of the energy consumption areas.

Figure 2 shows the geographical distribution of the differences in 40-day mean sea level pressure between the Megalopolis experiments and the average of the three control cases. Areas where the "signal to noise" ratio is greater than 5.0 are shaded. In MX01 (Fig. 2a), a big change occurs over an extended area covering eastern Siberia and most of Canada, its maximum being a 15 mb pressure increase over Alaska. The "signal to noise" ratio is greater than 5.0 over a large part of this area. The pressure increase also covers parts of the Pacific, as far south as 40°N. The effect in the vicinity of the American megalopolis (M1) is a 4 mb decrease right over this area. Over the Atlantic there is a 12 mb pressure increase, which exceeds the model variability. A decrease covers Greenland which, despite its magnitude of 12 mb, is not significant. The European megalopolis (M2) causes a big regional response. A 8 mb decrease occurs directly over the area and the ratio, r, is greater than 5.0 over central Europe and the Mediterranean sea. North of M2, a pressure increase occurs which increases further east with a maximum of 24 mb over the western part of the Soviet Union. There is no change directly over M3, but a big decrease downstream of this area covers parts of Siberia. M4, M5 and M6 also cause big regional responses. In particular, southeast Asia is covered by a large pressure decrease with r being greater than 5.0 in a big part of this area. As a general result it can be said that in almost all 6 areas the heat input causes large regional pressure decreases. The total sum of changes in MX01 is comparable with those in EX01, the magnitude and locations of the individual changes, however, are different.

The changes in mean sea-level pressure in MX02 (Fig. 2b) show strong similarities to those observed in MX01. The pressure increase over eastern Siberia and Canada is even larger than the increase in MX01. There is the same decrease over M1 but the changes over Greenland and over the Atlantic are much smaller than they were in the previous experiment. The "signal to noise" ratio of the increase over the Atlantic, therefore, is less than 5.0 in MX02. M2 causes a big pressure decrease which is only slightly smaller in magnitude but still exceeds, as in MX01, the model variability. North of M2 occurs another pressure increase but it is smaller than the one in MX01. The pressure decrease over Siberia in MX01 has only a small equivalent in MX02 which is basically shown by a change of sign in this area. M4, M5 and M6 still cause big regional changes, but they are not as big as in MX01 and exceed the model variability only in a much smaller area.

The model response in sea-level pressure to the 30 TW scenario of MX03 (Fig. 2c) is still similar to the previous experiments. The only area, however, where the "signal to noise" ratio is bigger than 5.0 is the vicinity of M2. Of the other areas which seem to be affected by the heat input, only the Atlantic and a large area northeast of M2 show strong changes which are also similar to those reported for MX01 and MX02. The changes over southeast Asia are again smaller than in MX02 and do not seem to be significant.

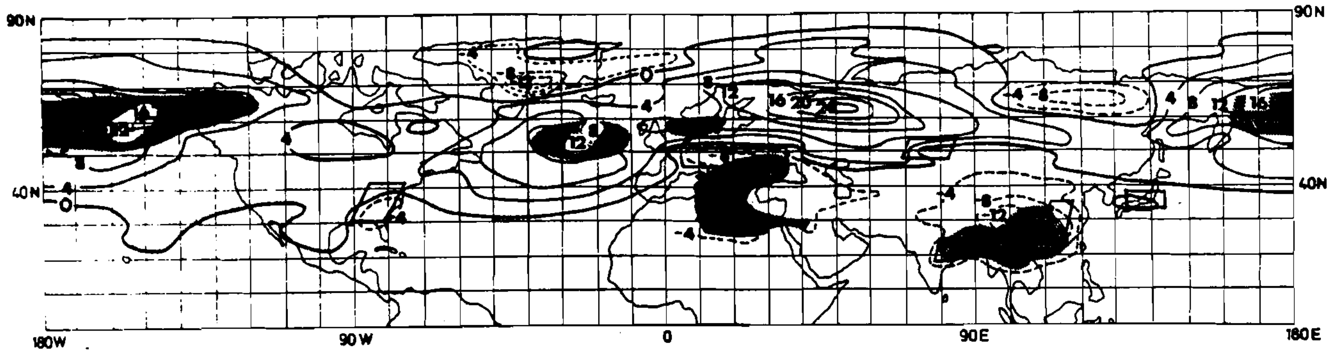

Figure 2a. MX01.

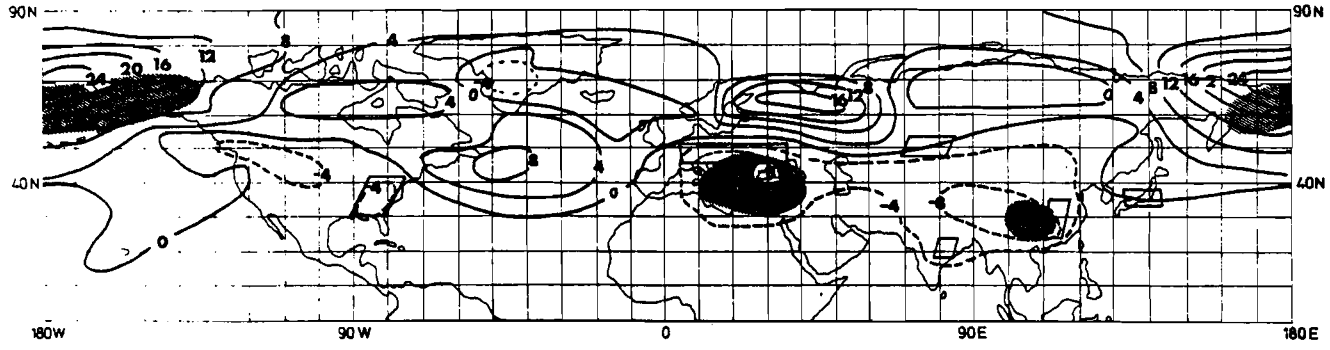

Figure 2b. MX02.

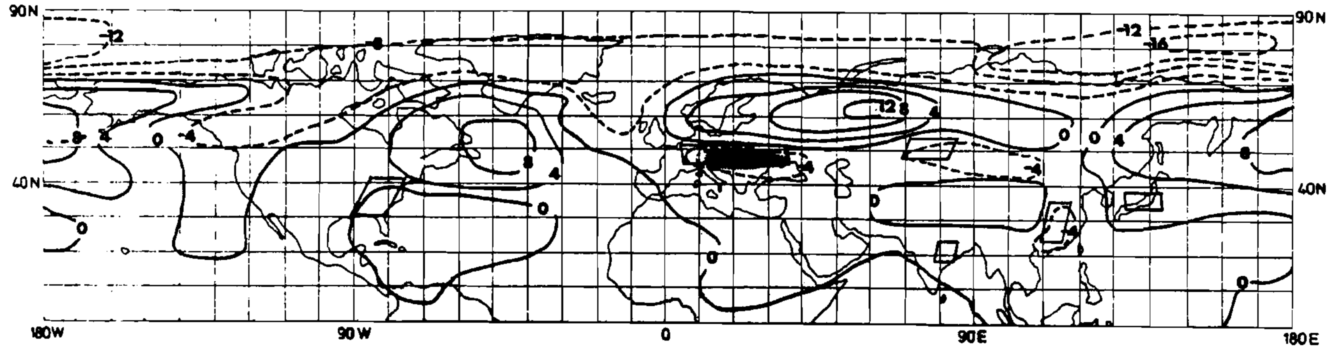

Figure 2c. MX03.

Figure 2. Geographical distribution of the differences between the Megalopolis experiments and the average of the three control cases in 40-day mean sea-level pressure. Shaded areas indicate where the "signal to noise" ratio is greater than 5.0 based on the standard deviation of the 40-day means. Units: mb.

In contrast to the other two experiments there is a pressure decrease over all of the polar area in MX03. However it is not possible to attribute any physical or statistical significance to this change.

Figure 3 shows the differences in 40-day mean height of the 500 mb surface between the Megalopolis experiments and the average of the three control cases. In MX01 (Fig. 3a), the largest changes are found over the northern Pacific, the Atlantic and Siberia, where the ratio is also greater than 5.0. Comparison of the changes in the height of the 500 mb surface with those in sea-level pressure show interesting similarities. The sea-level pressure increase over the Atlantic, western Siberia and Alaska, the decreases over the Soviet Union and the Mediterranean can be found again at the 500 mb surface. The pressure response over the U.S., southeast Asia and Greenland, however, have no parallels in the height field.

The geographical distribution of the differences between the height of the 500 mb surface of MX02 and the average of the control experiments is shown in Figure 3b. As already observed for the sea-level pressure, the changes in the height field are very similar for MX01 and MX02. It is again the area over eastern Siberia and Canada where the changes in MX02 are even larger than in MX01. Similar, but smaller changes also occur over the Atlantic, Europe and the Soviet Union. An additional change is the small decrease over the Pacific. As already observed for MX01, there are again similarities between the distributions of the sea-level pressure and the height of the 500 mb surface in MX02. Particularly Europe, the Atlantic and Siberia show a strong correlation between the two variables.

The changes in the height field in MX03 (Fig. 3c) are again somewhat different from the ones observed for MX01 and MX02. There is a decrease in the height field in the polar latitudes, a pattern which has already been observed for the sea-level pressure in MX03. Other changes occur over Canada, where they also exceed the model variability and over the Soviet Union. It can be stated, however, that the magnitude of change is much smaller in MX03 than in MX01 and MX02. Since the distribution of changes in MX03 shows only two small areas where the "signal to noise" ratio is greater than 5.0, it can in general be said that a heat input of 30 TW does not produce changes which can be distinguished from the noise of the model's inherent variability.

In Figure 4, the differences in 40-day mean temperature of the lowest atmospheric layer between the Megalopolis experiments and the average of the control cases are shown. In MX01 (Fig. 4a), large changes occur mainly over the continents. There is a 10°C cooling over Canada and Siberia, which is clearly related to the increase in sea-level pressure, with the ratio, r, being greater than 5.0 in parts of Siberia and over M3. A 6°C warming over Greenland, related to the decrease in sea-level pressure in this area, also has a high value of the "signal to noise" ratio.

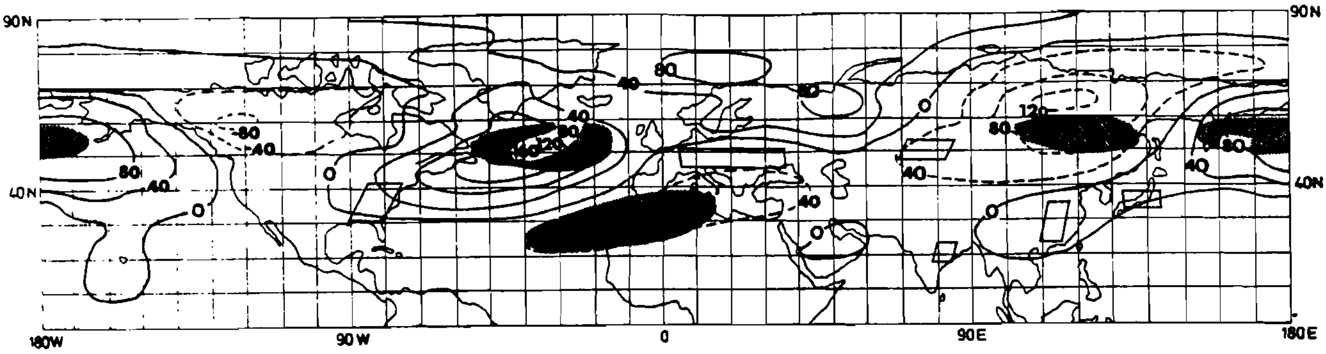

Figure 3a. MX01.

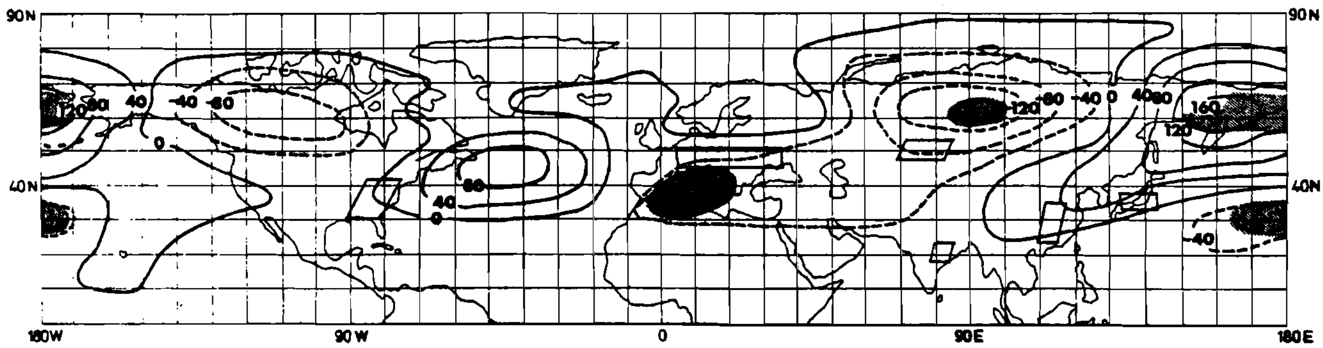

Figure 3b. MX02.

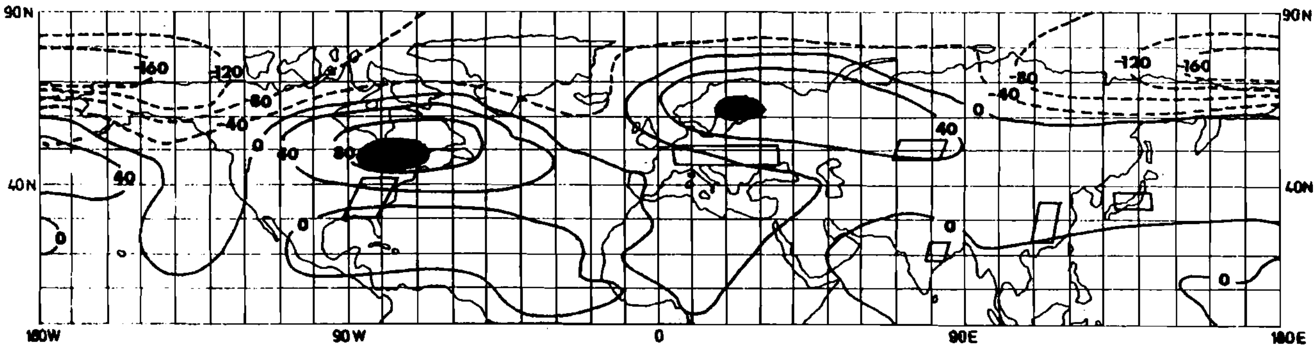

Figure 3c. MX03.

Figure 3. Geographical distribution of the differences between the Megalopolis experiments and the average of the three control cases in the 40-day mean height of the 500 mb surface. Shaded areas indicate where the "signal to noise" ratio is greater than 5.0 based on the standard deviation of the 40-day means. Units: dyn. m.

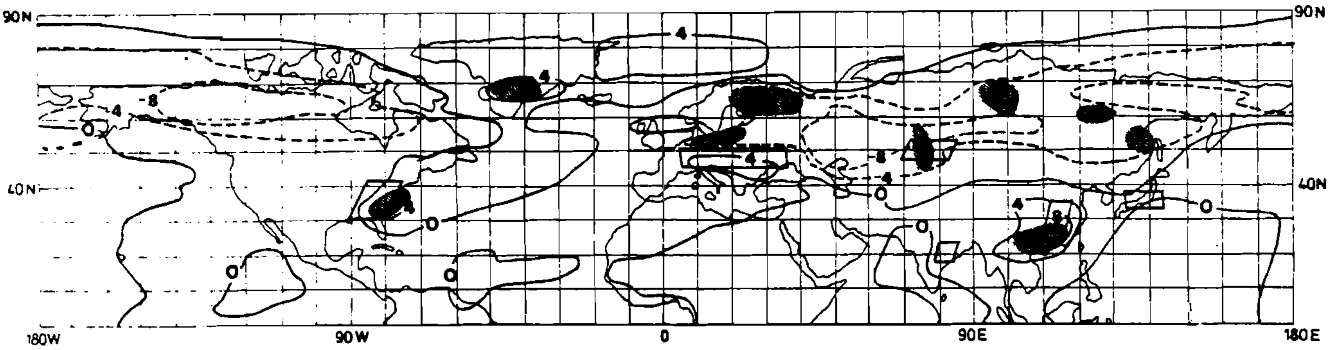

Figure 4a. MX01.

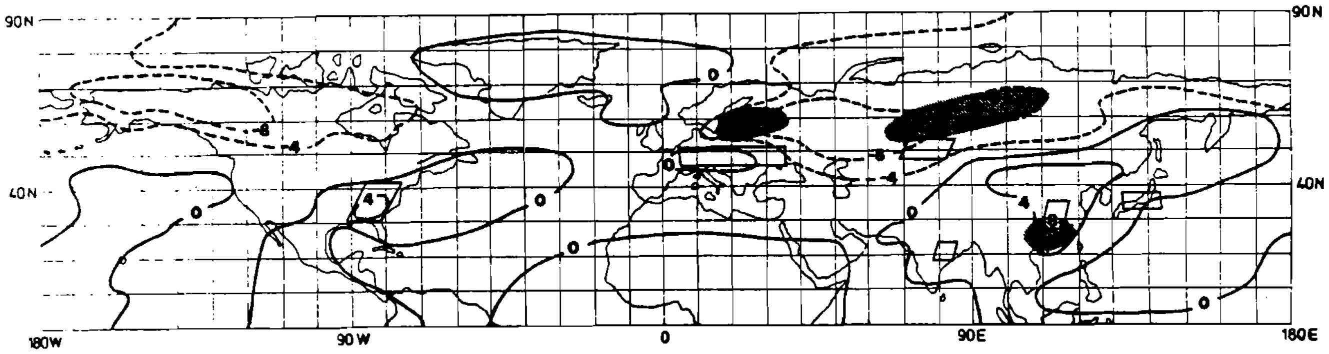

Figure 4b. MX02.

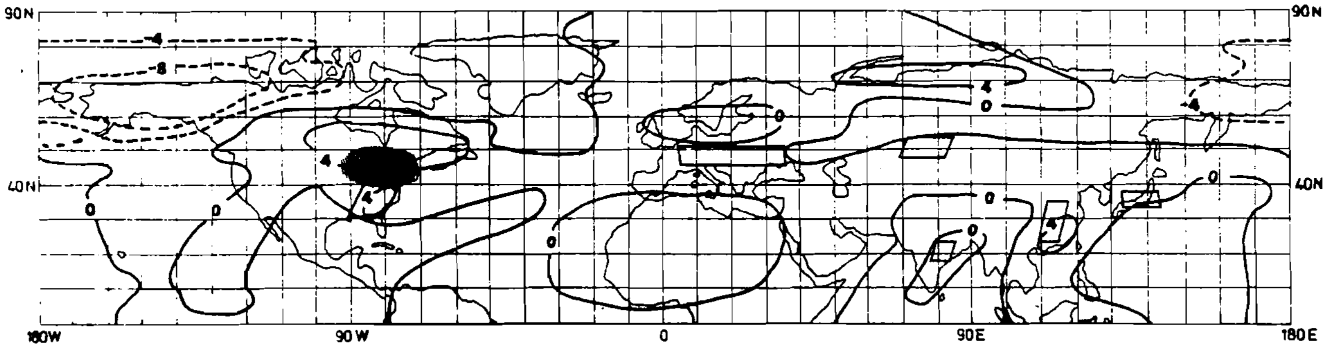

Figure 4c. MX03.

Figure 4. Geographical distribution of the differences between the Megalopolis experiments and the average of the three control cases in 40-day mean temperature of the lowest atmospheric layer. Shaded areas indicate where the "signal to noise" ratio is greater than 5.0 based on the standard deviation of the 40-day means. Units: ^{0}C.

As in EX01-EX05 the temperature response in areas away from the heat input is forced by pressure response. There is again a large, possibly significant impact in Europe with a maximum 4^0 warming over the megalopolis area. An 8°C increase over M5 and a 5°C warming over M1 exceed the model's inherent variability. Again, the big regional responses of the megalopolis areas should be noted. M1, M2 and M5 show large, possibly significant temperature increases which are also consistent with the fact that heat is being added in these areas.

Similar observations can be made for the temperature changes in MX02 (Fig. 4b). The changes occur mainly over the continents and are positive over almost all areas of heat input. Again, M1, M2 and M5 show large regional impacts which also exceed the model variability in the vicinity of M2 and M5.

The changes in the temperature distribution in MX03 are smaller than in the other experiments and there is only one area, north of M1, where the "signal to noise" ratio is greater than 5.0.

The geographical distribution of the differences in precipitation between the Megalopolis experiments and the average of the control cases (not illustrated) shows the largest changes in the tropics. This has been found already in the previous experiments and has been explained there. One consistent response in the energy parks experiments was the similar pattern of precipitation differences in the vicinity of park A. There was a decrease in precipitation in a band upstream of park A and an increase immediately downstream.

This pattern can to some extent also be found in the Megalopolis experiments. There are increases in precipitation downstream of M1, M2 and M5 and southeast of M4 in all experiments. A decrease occurs over the Atlantic upstream of M2 and an area upstream of M4. The impact of M4 and M5 on precipitation, however, must be considered with some caution because of the large inherent variability of the model's precipitation in this area. As already observed in the previous experiments for park A, it is seen that the precipitation increase on the downstream side of M1, M2, M4 and M5 is somehow associated with the pressure decrease in these regions. On the upstream side of the areas mentioned, the pressure changes can not be consistently associated with the changes in precipitation. Only the pressure increase over the Atlantic relates to the large precipitation decrease in this area. As it was noted for the other variables, the overall impact on precipitation decreases as well if the heat input is smaller.

It is worthwhile to compare the above results with those of the NCAR Megalopolis experiment (Llewellyn and Washington, 1977). The latter showed a 12°C warming over the energy consumption area. The only other big change reported was a 6°C cooling over Greenland. This is quite a different response compared to MX01 where there was a change of opposite sign over Greenland and only a small change over M1. The changes in MX01, however, are a hemispheric response to heat inputs in six areas as compared with one megalopolis in the NCAR experiment.

CONCLUSIONS

Three experiments have been run with the atmospheric general circulation model of the U.K. Meteorological Office to investigate the response of the simulated atmospheric circulation to an input of heat totaling 300, 50 and 30 TW at six megalopopis locations in the northern hemisphere. The results of these experiments can (to a limited extent) be compared with those of earlier IIASA experiments with the same model investigating the response to ocean energy parks.

It is found that when the heat input of 300 TW is spread over six areas the hemispheric response is comparable to that when the heat input is concentrated at only two energy parks. There is still a sufficient number of areas over which the "signal to noise" ratio is greater than 5.0 to suggest that there is a significant model response to the megalopolis heat input. A further result is the strong regional response of some of the megalopolis areas.

As in the earlier model experiments there are large coherent areas of change in the sea-level pressure and 500 mb height fields and distribution of temperature in the lowest atmospheric layer, not only over the area of heat input but elsewhere in the hemisphere.

If the heat input is reduced to 50 TW, the impact decreases only slightly, emphasizing again the strong nonlinear behavior of the model atmosphere. There are also strong similarities in the response to 300 TW and that to 50 TW. A further reduction of the waste heat release to 30 TW, a tenth of the amount used in MX01 and some of the previous IIASA energy parks experiments, seems to bring the response of the model atmosphere closer in the neighborhood of the model climate, as defined by the average of the three control experiments.

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