

R-1324-ARPA
March 1974

The Atmospheric Response to a Stratospheric Dust Cloud as Simulated by a General Circulation Model

E. S. Batten

A Report prepared for
DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

The research described in this Report was sponsored by the Defense Advanced Research Projects Agency under contract No. DAHC15-73-C-0181. Reports of The Rand Corporation do not necessarily reflect the opinions or policies of the sponsors of Rand research.

R-1324-ARPA

March 1974

The Atmospheric Response to a Stratospheric Dust Cloud as Simulated by a General Circulation Model

E. S. Batten

A Report prepared for
DEFENSE ADVANCED RESEARCH PROJECTS AGENCY



PREFACE

There has been concern that man's activities might produce deleterious changes in the weather and climate. This report describes and assesses the results of an initial experiment, using the Mintz-Arakawa general circulation model, designed to simulate the perturbations produced by a stratospheric dust cloud.

The work is part of the studies undertaken under the Rand/ARPA Climate Dynamics Program. For related work, see Rand publications R-886-ARPA, *Global Turbidity Studies: I. Volcanic Dust Effects—A Critical Survey* (D. Deirmendjian, 1971); R-877-ARPA, *A Documentation of the Mintz-Arakawa Two-Level Atmospheric General Circulation Model* (W. L. Gates et al., 1971; R-1263-ARPA, *The Black Cloud Experiment* (A. B. Kahle and D. Deirmendjian, 1973); and "An Experiment on the Sensitivity of a Global Circulation Model," in *J. Appl. Meteorol.* (M. Warshaw and R. R. Rapp, 1973).

The author would like to thank D. Deirmendjian, A. B. Kahle, and R. R. Rapp for helpful suggestions, and for carefully reviewing and commenting on the manuscript.

SUMMARY

The Rand version of the Mintz-Arakawa General Circulation model has been used to investigate the initial atmospheric response to a stratospheric dust cloud spread uniformly in a zone between 25°N and 75°N. In the experiment to be discussed, the dust cloud is assumed to consist of particles 2 μ m in diameter or smaller, totaling 4×10^{-2} km³. This volume of dust is equal to the estimated volume ejected into the stratosphere by the 1883 eruption of Krakatoa. The stratospheric dust cloud is assumed to perturb the atmosphere by attenuating the solar radiation and by stimulating the precipitation process.

The model was integrated for a simulated period of 60 days corresponding to the months of January and February. The results were compared with a control experiment starting from the same initial conditions and simulating the same period. The following anomalies in temperature, precipitation, and atmospheric circulation were noted. In the atmosphere and at the surface beneath the dust cloud, the temperature decreased 2 to 3°C and the normal wintertime land/ocean temperature contrasts were increased. Despite the specification of a 20-percent increase in the rate of precipitation, the total precipitation at latitudes affected by the cloud did not change significantly. However, the latitudinal distribution of precipitation was modified. The precipitation at high latitudes (46°N to 74°N) actually decreased by about 20 percent, while at low latitudes (26°N to 46°N) the precipitation increased by about 23 percent. Although some of the anomalous precipitation patterns can be explained by anomalies in the evaporation, most are a direct result of changes in the circulation and moisture flux. The joint effects of decreasing the solar radiation and increasing the precipitation resulted in a weakening of the midlatitude Ferrel circulations, a decrease in the baroclinicity (and therefore in northward eddy transports of moisture) at high latitudes and an increase in the baroclinicity (and therefore northward eddy transports) at low latitudes.

CONTENTS

PREFACE.....	iii
SUMMARY	v
Section	
I. INTRODUCTION.....	1
II. DESIGN OF THE EXPERIMENT.....	2
Attenuation of Solar Radiation	2
Modification of Precipitation	3
III. RESULTS.....	4
Changes in the Radiation Budget.....	4
Moisture Balance Anomalies.....	9
Circulation Anomalies.....	13
IV. DISCUSSION.....	15
REFERENCES	17

I. INTRODUCTION

Man has become increasingly concerned with possible climatic changes produced by natural causes or inadvertently caused by human activities (SCEP, 1970; SMIC, 1971). With the present state of the art in general circulation models (GCMs), one has a tool with which to begin a more systematic evaluation of man's influence on his environment. To be sure, none of the atmospheric simulations produced by GCMs available today can be considered as totally accurate representations of the real atmosphere. The GCMs are, however, capable of simulating many of the important interactions taking place in the real atmosphere and capable of duplicating many details of the general circulation. It seems appropriate then to begin testing the GCMs' usefulness as a tool in climate studies. By comparing atmospheric simulations containing hypothetical anomalies with a control simulation that starts from the identical initial condition, perhaps one can gain both a better appreciation for the sensitivity of the model and some understanding of the perturbations produced by the anomalies. Several such experiments have already appeared in the literature (Washington, 1971 and 1972; Spar, 1973; Warshaw and Rapp, 1973; Kahle and Deirmendjian, 1973).

One of the above studies, *The Black Cloud Experiment* (Kahle and Deirmendjian, 1973), simulated a global reduction of solar radiation which, under some conditions, could be attributed to a turbid layer above the top of the model atmosphere. A turbid stratosphere has frequently been invoked to explain variations in the transmission and absorption of solar radiation leading to long-term changes in climate. Some proposed sources of the turbidity are volcanic eruptions (Humphreys, 1940, and Wexler, 1956), nuclear explosions (Stonier, 1963), and recently, particulate matter produced by supersonic transports (SCEP, 1970). It is possible that, under some conditions, the stratospheric turbidity layer would be confined primarily to one hemisphere either as a result of the location of the injection or by redistribution by the stratospheric circulation. As an interesting departure from the global nature of the Black Cloud Experiment, the experiment discussed here will investigate the effects of a stratospheric dust layer confined to the northern hemisphere.

It has also been suggested that particulate matter falling from the stratosphere to the troposphere might influence the precipitation process (Wexler, 1953 and 1956; Menzel, 1953, and Batten, 1966). Thus, in addition to attenuating the solar radiation, this experiment assumes that the dust cloud will act to stimulate the precipitation process.

The Mintz-Arakawa GCM described by Gates et al. (1971) was used to perform the integration. As the results of the experiment are presented, we will be concerned not only with their interpretation as an anomalous event but also with how specifications of future models might improve interpretations of future experiments.

II. DESIGN OF THE EXPERIMENT

In addition to asking how human activities might produce climatic changes, one might ask how climatic changes influence human activities. When evaluating this inverse question, it would be helpful to have some estimates of the upper limits of climatic change. Accordingly, this experiment will employ a "worst case" strategy. That is, extreme values of stratospheric dust loading and upper limit estimates of cloud seeding effects will be assumed.

It has been estimated that the 1883 eruption of Krakatoa produced a volume of dust totaling about $4 \times 10^{-2} \text{ km}^3$ and consisting of particles $2\mu\text{m}$ in diameter or smaller. However, the Krakatoa dust was confined to the zone between 30°S and 30°N . We are assuming in this experiment that the dust will be confined to a latitude belt of 25°N to 75°N , approximately half the area covered by the Krakatoa cloud.

ATTENUATION OF SOLAR RADIATION

Deirmendjian (1971) evaluated the role of the volcanic dust in increasing atmospheric particulate turbidity. On the bases of his conclusions, (Deirmendjian, 1973) he also provided a "dirty cloud" model for use in a "worst case" experiment. The rationale for the "dirty cloud" model can be found in the above-mentioned report. Here I will only discuss the changes to the Mintz-Arakawa model.

The solar radiation simulated in the Mintz-Arakawa model is divided into two parts (see Gates, et al., 1971, Chapter II, Section G). The radiation of wavelength $\lambda < 0.9\mu\text{m}$ is assumed to be subject to Rayleigh scattering only; that of wavelength $\lambda \geq 0.9\mu\text{m}$ is assumed to be subject to absorption only in a clear atmosphere. The part subject to scattering is given by $0.651 S_0$ where S_0 is the solar constant. Only the part subject to scattering is assumed to be affected in this experiment. Deirmendjian's dirty cloud then consists in assigning the following mean optical thicknesses over the short wave range:

$$\bar{\tau}_D = 1.05 \quad \text{"blue sun" stage,}$$

$$\bar{\tau}_D = 0.92 \quad \text{"Bishop's ring" stage,}$$

where the first is representative of the initial few weeks after the Krakatoa eruption, and the second to the more stable stage. In this experiment the Bishop's ring mean optical thickness is used. Thus the solar radiation subject to scattering is reduced by a factor

$$e^{-\bar{\tau}_D} \simeq 0.4 \tag{1}$$

amounting to a loss of the total incoming radiation under the dust cloud given by

$$0.651(1 - e^{-\bar{\tau}_D})S_0 \simeq 0.39 S_0 \tag{2}$$

This amount of attenuation represents a decrease in the globally averaged incoming radiation of about 5 percent, if the dust cloud is in the winter hemisphere, and of about 15 percent if it is in the summer hemisphere. Since the experiment discussed here is simulating northern winter conditions, the net attenuation is comparable to that assumed in the Black Cloud experiment (Kahle and Deirmendjian, 1973). How-

ever, in that experiment, the solar radiation was attenuated globally, whereas in this one, the attenuation is confined to a broad belt in the northern hemisphere.

MODIFICATION OF PRECIPITATION

The Bergeron ice-crystal process is one mechanism by which cloud droplets grow to sizes large enough to fall as some form of precipitation. Briefly, the ice-crystal theory states that ice crystals, when surrounded by supercooled water droplets, will grow at the expense of the water droplets, since vapor pressure is less over ice than over water. In other words, when the air is saturated with respect to water it is supersaturated with respect to ice, and condensation on the ice crystal will result. Water droplets are observed in clouds often at temperatures as low as -20°C and sometimes -35°C ; hence if ice crystals are introduced into the cloud, the stage is set for creation of precipitation. As in the case of condensation, the initiation of freezing requires a suitable nucleus. The most active ice nuclei are nonsoluble, wettable particles of dust and soil about $1\mu\text{m}$ in radius (Mason, 1960). The prevalence of liquid-water clouds down to -15°C suggests that efficient ice nuclei are rare, at least at the altitudes where ice crystals "seed" the supercooled clouds. It is not unreasonable to suspect that the efficiency of the Bergeron process might increase as the stratospheric dust slowly falls into the upper troposphere. It is also possible that the dust may inhibit precipitation by "over-seeding" the clouds. In this experiment we assume that the precipitation will increase by approximately 20 percent in the zone between 25°N and 75°N .

The Mintz-Arakawa model simulates three types of precipitation. Large-scale precipitation occurs when the relative humidity at a point exceeds 100 percent. The amount of large-scale precipitation is equal to the amount of moisture that must be removed to reduce the relative humidity to 100 percent. In this experiment, the increased precipitation is simulated by lowering the threshold for rain to 99.675 percent relative humidity. In a separate study it was determined that lowering the threshold to this value was equivalent to an increase in precipitation of 20 percent.

The other two types of precipitation, middle-level and penetrating convective rain, are similar in that they both require regions of moist convective instabilities in the atmosphere (Gates, et al., 1971, Chapter II, Section F). The amount of convective precipitation is determined by the amount of condensation required to relieve the instability through the release of latent heat. Not all of the instability is removed at once, the rate being controlled by a time constant determined by the parameterized amount of convective activity occurring in each grid cell. In this experiment, the convective precipitation is assumed to increase by 20 percent, which is equivalent to decreasing the e-folding time for the decay of the moist convective instability. In other words, we have made the convective activity more vigorous.

III. RESULTS

The data used in this Report are from Control III and the Stratospheric Dust Cloud experiment (experiment 17). The Control III was integrated for a 90-day period that corresponds to the months of December, January, and February. After the changes to the model outlined in Section II were made, experiment 17 was integrated for a 60-day period starting with the conditions at the end of the first 30 days of Control III. This period corresponds to 31 December through 28 February. The results of experiment 17 at best represent the model's initial responses to the simulated stratospheric dust cloud.

The period chosen for analysis was a 25-day period (21 January through 14 February). The choice of this period was dictated by the occurrence of unusually high and unrealistic rates of precipitation in both Control III and experiment 17. In Control III extremely high rates of precipitation were encountered in a small area on the northwest coast of South America. In experiment 17 similar conditions occurred over the Amazon Basin. Thus only a 25-day average was analyzed to eliminate as much as possible the influence of these events on the interpretation of the results. The cause of the events will be the subject of a future investigation.

CHANGES IN THE RADIATION BUDGET

Since we have assumed that the dust cloud affects only the radiation subject to scattering by the atmosphere, the initial effect of the cloud will be to decrease the radiation absorbed at the ground. The imposed anomaly in the solar radiation absorbed at the ground (S_g) is shown by the upper pair of curves in Fig. 1. The solid line gives S_g for the control run, and the dashed line gives S_g for this experiment. The difference between these two curves essentially reflects the attenuation indicated by Eq. (2).

The lower pair of curves in Fig. 1 gives the net radiation gained at the ground (solar radiation absorbed less the long-wave radiation lost by the ground). The normal winter pattern for the net radiation gained at the ground is demonstrated by the R_g (net) curve for the control; the ground in polar regions cools radiatively in winter while the ground in lower latitudes is warmed radiatively. The effect of the anomaly produced in the radiation budget by the dust cloud is to extend the region of radiative cooling southward to 30°N. The difference between R_g (net) curves represent the radiation anomaly imposed on the earth-atmosphere system by the dust cloud.

The way in which the radiation anomaly is communicated to the more tangible meteorological variables of the lower boundary, and thence to the atmosphere, is partially restricted by assumptions made in formulating the numerical model. In the Mintz-Arakawa model, ocean temperatures are assumed to be constant in time. In effect, we are assuming an infinite heat capacity for the ocean. On the other hand, over the land, zero heat capacity is assumed, and the ground temperatures there are determined from a balance between net radiation at the surface, the heat loss by evaporation, and the sensible heat flux from the surface. Thus ground temperatures over land are permitted to cool in response to the imposed radiation anomaly, whereas ocean temperatures remain fixed.

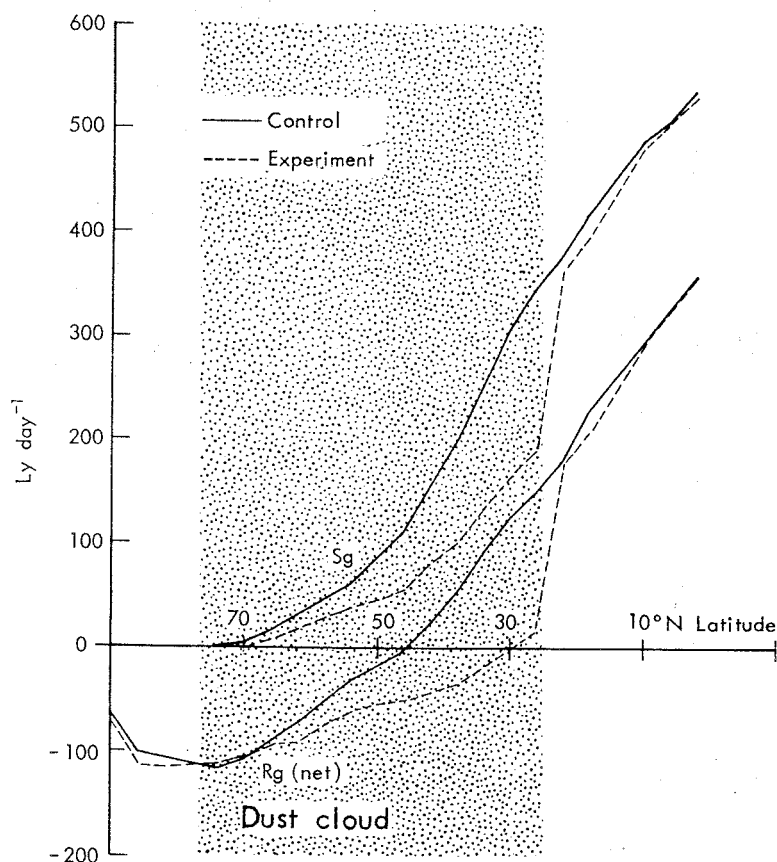


Fig. 1—Radiation budget at the ground. S_g is the solar radiation absorbed at the ground, R_g (net) is the net radiation at the ground (solar long wave).

The anomalies (experiment 17 minus Control III) of the zonal average ground temperature over land are shown in Fig. 2. The ground temperatures over land beneath most of the dust cloud have been decreased by 2 to 4 degrees. The large anomaly near the North Pole is probably due to the normal variability of the atmosphere and not a result of the experiment. Similar large fluctuations of ground temperature have been observed in data from earlier model experiments.*

Although the zonal average ground temperature of the land masses as a general rule has decreased, local exceptions to this rule can be found in areas of increased cloudiness. In areas of a positive cloudiness anomaly, the amount of long-wave radiation trapped in the lowest layer and returned to the surface has increased (the "greenhouse" effect), thus counteracting some of the cooling due to the loss of solar radiation at the surface. The zero ground temperature anomaly at 70 degrees latitude and the minimum anomaly near 40 degrees latitude, shown in Fig. 2, result from belts of increased cloudiness. As we shall see later, the southern belt of increased cloudiness is associated with a region of increased precipitation.

* See, for example, Warshaw and Rapp (1973) and Kahle and Diermendjian (1973).

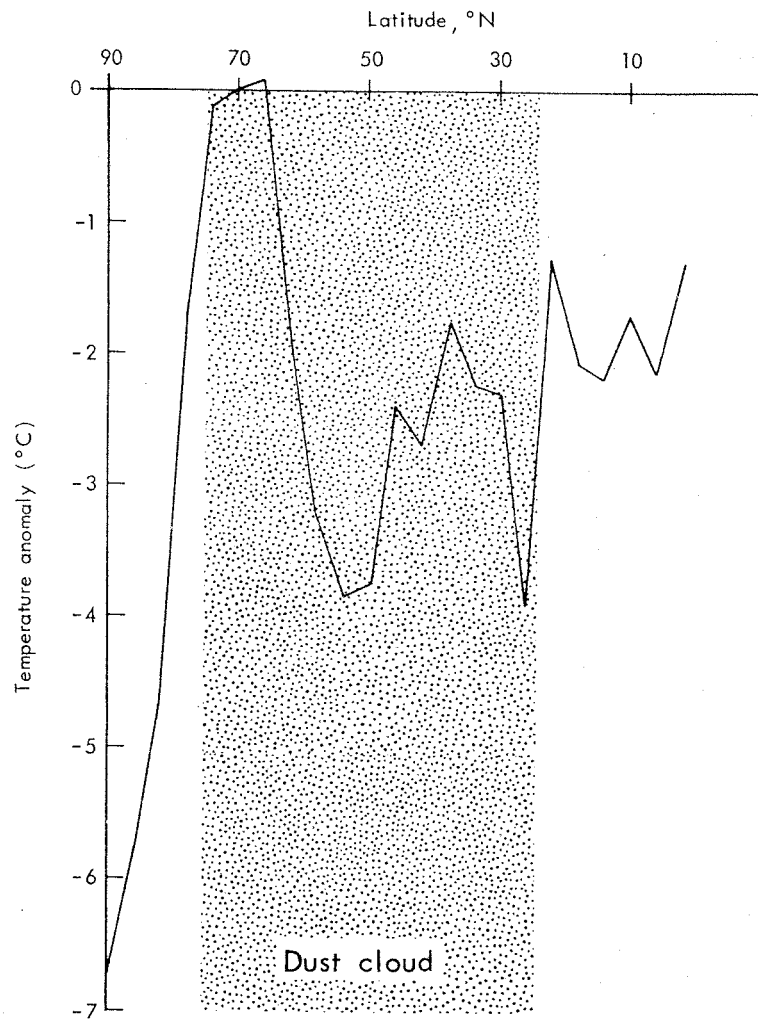


Fig. 2—Zonal average ground temperature anomaly (°C)

The anomalies in the ground temperature produced by the dust cloud are communicated to the atmosphere principally through the flux of sensible heat from the ground. On a long-term average, the net loss of radiation in the atmosphere is balanced by the transfer of the excess energy received at the surface through the processes of sensible and latent heat flux to the atmosphere. During winter, air passing over the land masses is cooled from below and that passing over the oceans is warmed from below. During summer the roles are reversed; the ocean acts as a heat sink and the land as a source. The sensible heat flux anomaly given in Fig. 3 shows that the dust cloud has magnified the normal winter role of the ocean as an atmospheric heat source and the land as a heat sink.

The effect of these anomalous sources and sinks on atmospheric temperature is shown in Fig. 4 for the surface air temperature anomaly and Fig. 5 for the 800 mb temperature anomaly. At both the surface and 800 mb the air over the land has

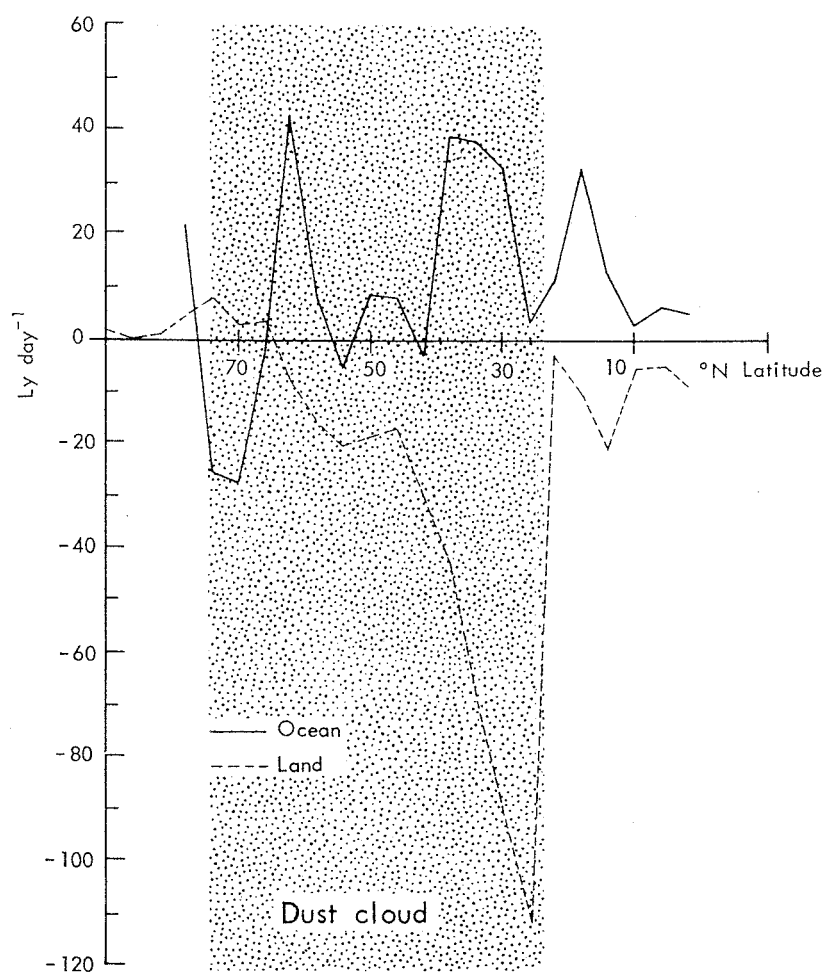


Fig. 3—Zonal average sensible heat flux anomaly (ly day⁻¹). Positive values represent an increase flux to the atmosphere

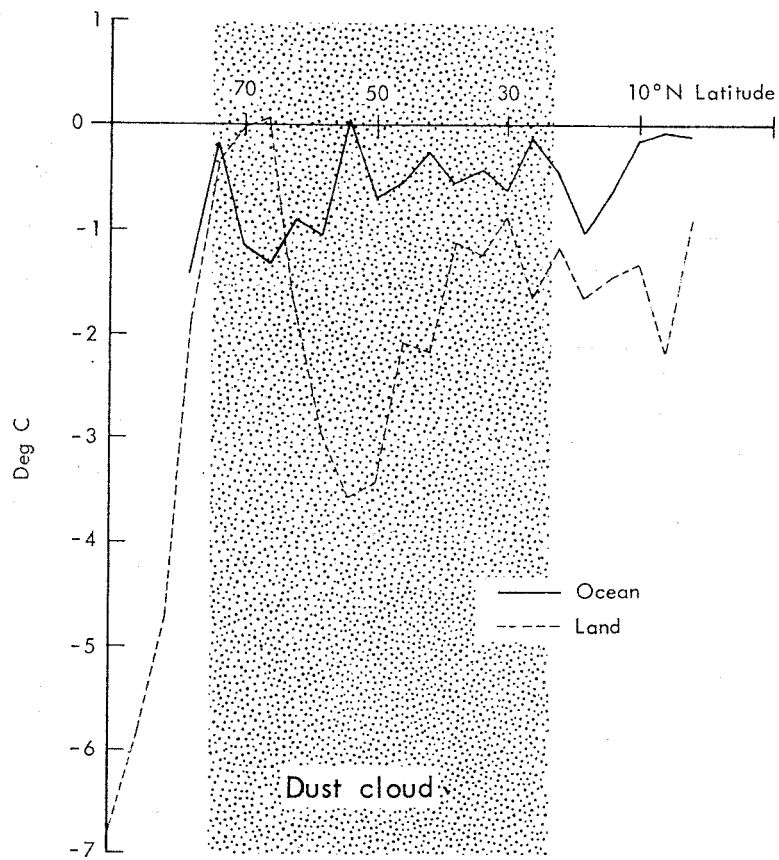


Fig. 4—Zonal average surface air temperature anomaly (°C)

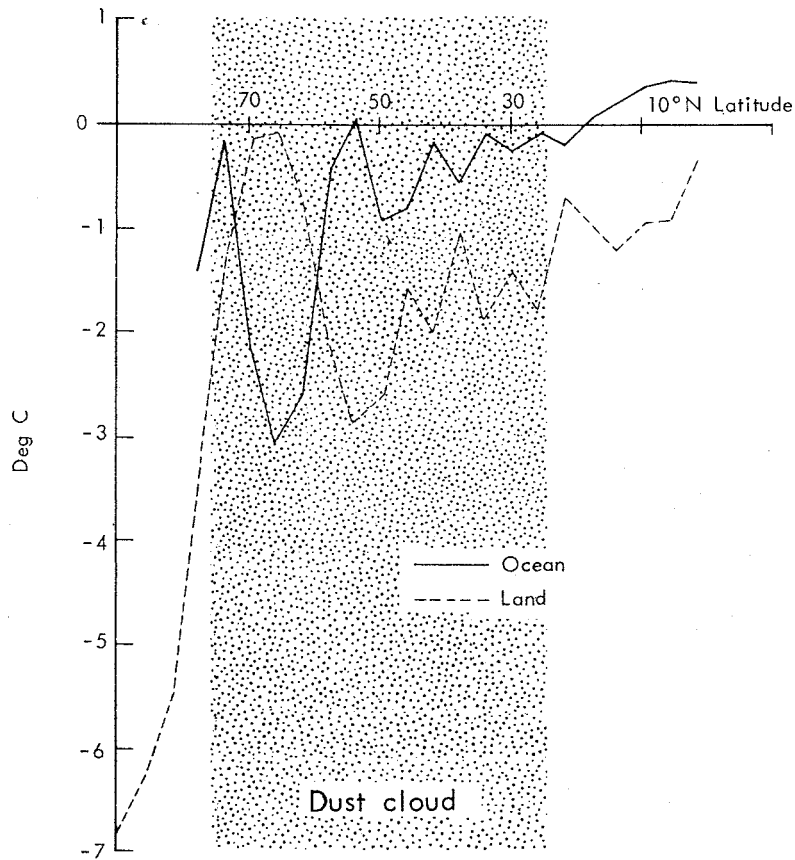


Fig. 5—Zonal average 800 mb temperature anomaly (°C)

cooled relative to the air over the ocean. This magnified land-ocean temperature contrast is not evident at the 400 mb level.

MOISTURE BALANCE ANOMALIES

This experiment postulates a 20 percent increase of precipitation in the region beneath the dust cloud (25°N to 74°N). In nature precipitation normally exceeds evaporation in the region north of 35°N. This deficit of moisture in the midlatitude storm belt is made up by a net northward flux of water vapor from the subtropical region where evaporation exceeds precipitation. The latitude of zero northward flux of water vapor lies near 25°N. Hence, north of 25°N, precipitation is in balance with evaporation. For the 20 percent increase of precipitation in the experiment to be maintained for any extended period of time, either the evaporation must increase, the moisture flux patterns must change, or both must change to accommodate the increase.

Figure 6 gives the precipitation, evaporation, and moisture flux-convergence anomalies produced by the dust cloud. We note that the precipitation (Fig. 6a) has increased between 26°N and 46°N. But, despite the conditions specified in the experi-

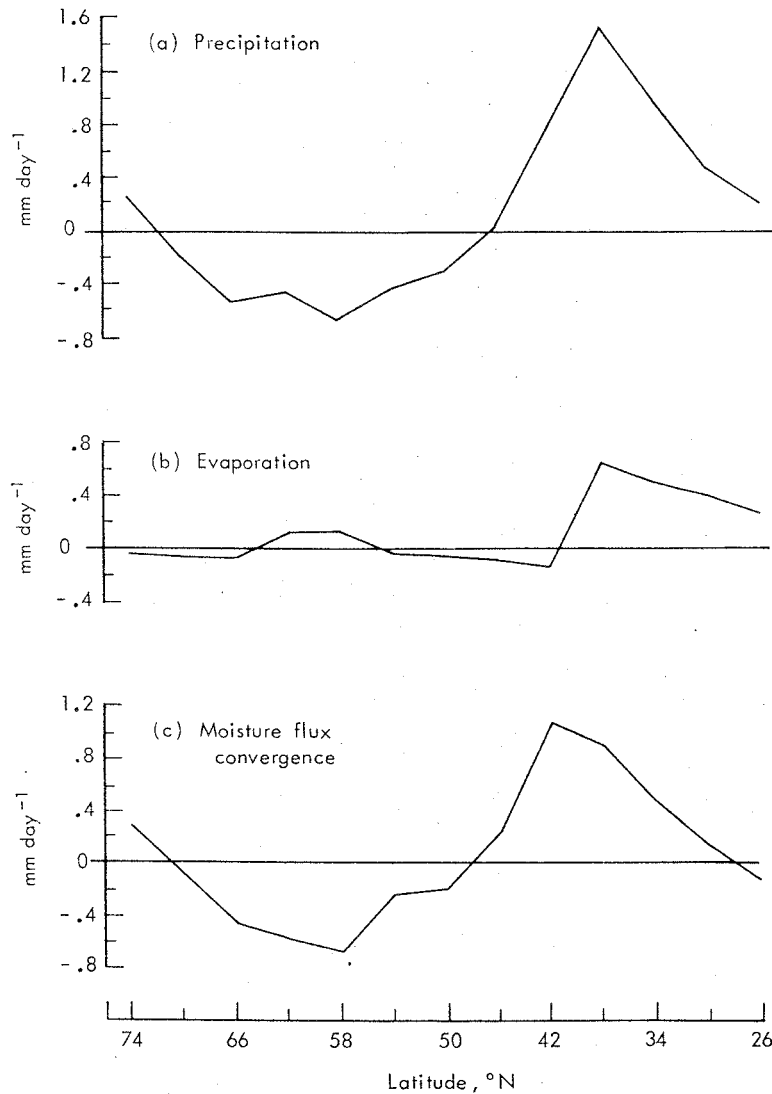


Fig. 6—Moisture balance anomalies

ment, the precipitation has decreased in the latitude belt between 46°N and 74°N. The anomaly at low latitudes (26°N—46°N) beneath the dust cloud represent a 22.8-percent increase and that at high latitudes (47°N—74°N) a 19.5-percent decrease in precipitation. The total precipitation beneath the dust cloud has increased slightly. The slight increase in precipitation over all latitudes affected by the cloud is not statistically significant. However, the decrease at high latitudes is significant at the 5-percent level and the low-latitude increase is significant at the 1-percent level.

Some of the moisture (39 percent) for the increase in precipitation at low latitudes is supplied by an increase in evaporation (Fig. 6b). At higher latitudes the evaporation is substantially unchanged. The remainder of the precipitation increase at low latitudes (61 percent) and the decrease in precipitation at high latitudes must, therefore, result from changes in the pattern of moisture flux.

Figure 6c gives the moisture flux-convergence anomaly. At high latitudes almost all of the decrease in precipitation results from a decreased convergence of moisture into the region. The moisture balance for the southern and northern regions beneath the dust cloud are summarized in Table 1.

Table 1
MOISTURE BALANCE BENEATH THE CLOUD
(all units in mm day^{-1})

		26°N to 46°N	50°N to 74°N
Precipitation	Control	17.536	11.628
	Experiment 17	21.472	9.361
	Anomaly	+3.936	-2.267
Evaporation	Control	24.820	4.840
	Experiment 17	26.357	4.863
	Anomaly	+1.536	+0.023
Moisture Convergence	Control	-7.429	6.620
	Experiment 17	-4.800	4.641
	Anomaly	+2.629	-1.979

The net effect of the dust cloud has been to produce a low-latitude belt of increased precipitation and a high-latitude belt of decreased precipitation. Most of the change in the precipitation pattern has been a result of changes in the moisture flux and thus of changes in the circulation. To explore the nature of the changes in the circulation patterns, the moisture flux for the control and the experiment are shown in Fig. 7. While the moisture flux given in Fig. 7 is about a factor of 2 larger than is observed in nature, the latitude distribution is reproduced fairly well. The important features of Fig. 7 are the increased northward flux south of about 40°N and the decreased northward flux north of 40°N. These two regions correspond to the regions of convergence and divergence shown in Fig. 6c. The net moisture flux can be considered to be the sum of the flux due to the mean meridional circulation and the flux due to eddies both standing and transient. This division is shown in Fig. 8 displayed as an anomaly (experiment minus control).

The solid curve in Fig. 8 is the total moisture-flux anomaly and is the difference between the two curves in Fig. 7. The dashed curve is the moisture flux due to the mean meridional circulation. As can be seen, the mean meridional circulation increases the southward flux of moisture from beneath the dust cloud. Exceptions are found near 70°N and 30°N, where small positive values are shown (northward flux). Thus the mean meridional circulation does not supply the moisture for the southern rain belt. The convergence of moisture there is provided by an increase in the eddy flux of moisture (dot and dash curve of Fig. 8). The mean meridional circulation and a southward eddy flux contribute equally to the northern region of moisture divergence.

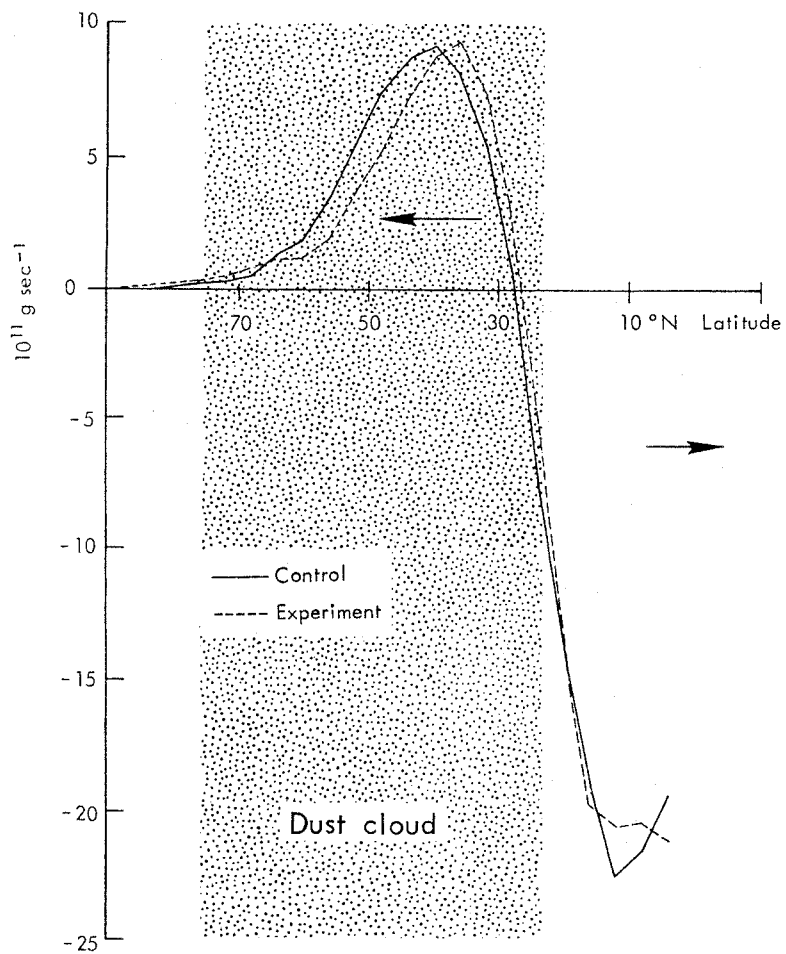


Fig. 7—Moisture flux $10^{11} \text{ g sec}^{-1}$: Positive values represent a northward flux. Negative values represent a southward flux

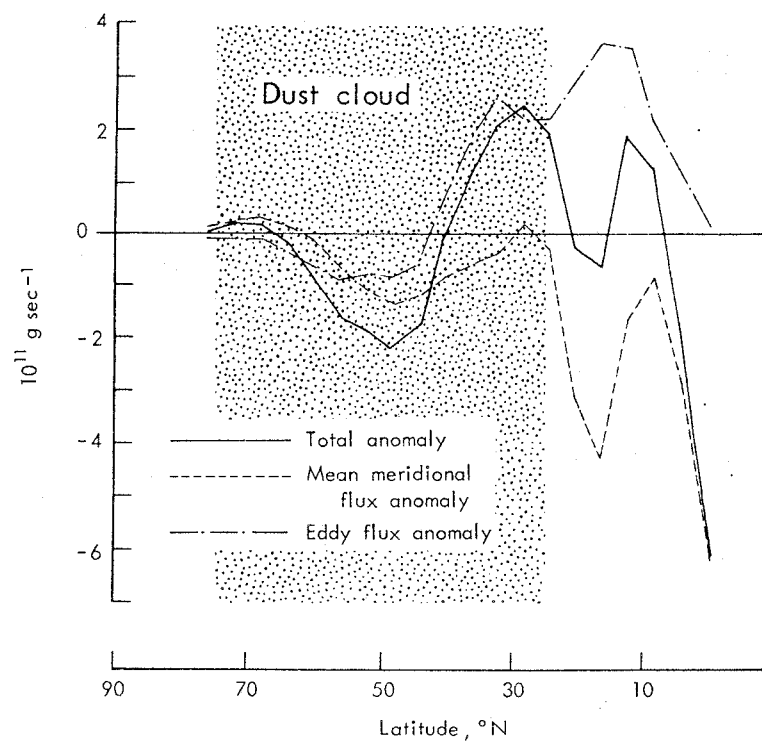


Fig. 8—Moisture flux anomaly ($10^{11} \text{ gm sec}^{-1}$)

CIRCULATION ANOMALIES

The anomalies in the mean meridional circulation and the eddy activity suggested by Fig. 8 can be seen more clearly in Figs. 9, 10, and 11. Fig. 9 shows the zonally averaged mass flux for the control. A strong Hadley cell is evident at low latitudes and a weak Ferrel cell at midlatitudes. Figure 9 is similar to the results from an earlier control discussed by Gates (1972). Figure 10 gives the zonally averaged mass-flux anomaly produced by the experiment. Near the center of the region beneath the dust cloud, the anomaly shows that a strong direct-circulation cell (Hadley type) has been produced with weak indirect cells (Ferrel type) near the northern and southern boundaries. The rising and sinking branches of this anomalous circulation correspond exactly to the wet and dry belts as shown in Fig. 6a suggesting that the maintenance of this circulation is to a large extent due to the release of latent heat in the southern wet zone. As shown in Fig. 8, however, the moisture for the wet zone is supplied by an increased eddy flux. The increased eddy activity accompanies an increase in the baroclinicity produced by latent heat release in the ascending branch of the circulation, coupled with cooling at higher latitudes induced by the surface heat sink discussed in the section on the radiation budget. The stronger north-south temperature gradients at 800 mb can be inferred from Fig. 5. Other measures of the changing patterns of baroclinicity, shown in Fig. 11, are the anomaly in the vertical wind shear and eddy kinetic-energy anomaly. Both the wind shear and the eddy kinetic energy show a decrease in the same high latitude belt where a decrease in northward eddy flux of moisture was observed (Fig. 8). At lower latitudes, the increased wind shear and eddy kinetic energy corresponds to the region of increased northward eddy flux of moisture.

In summary, the joint effects of decreasing the solar radiation and increasing the precipitation has led to the weakening of the Ferrel circulation cell beneath the dust cloud. The baroclinicity has decreased beneath the northern portion of the dust cloud and increased beneath the southern portion. The baroclinic zone is thus moved to a position near the southern boundary of the dust cloud, where the associated eddies provide the transport mechanism that feeds moisture to a belt of increased precipitation.

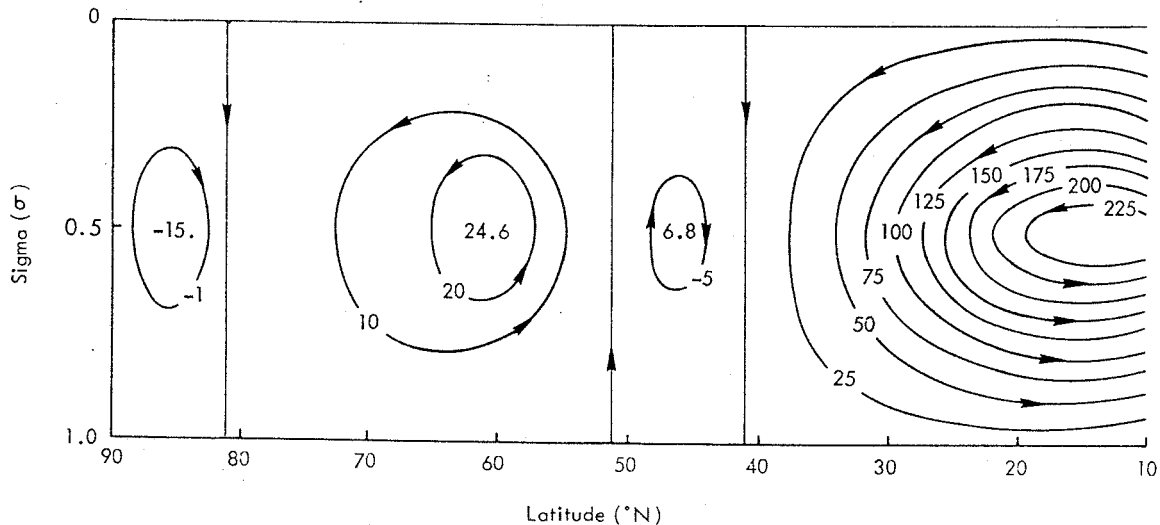


Fig. 9—Zonally averaged mass flux (10^{12} g sec $^{-1}$) for the control

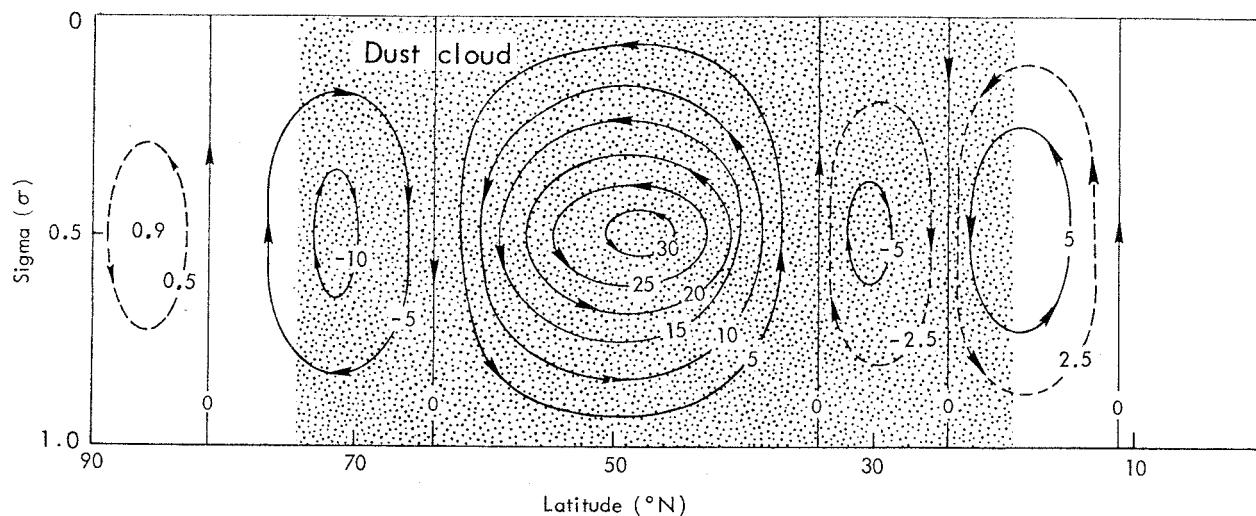


Fig. 10—Zonally averaged mass flux anomaly ($10^{12} \text{ g sec}^{-1}$)

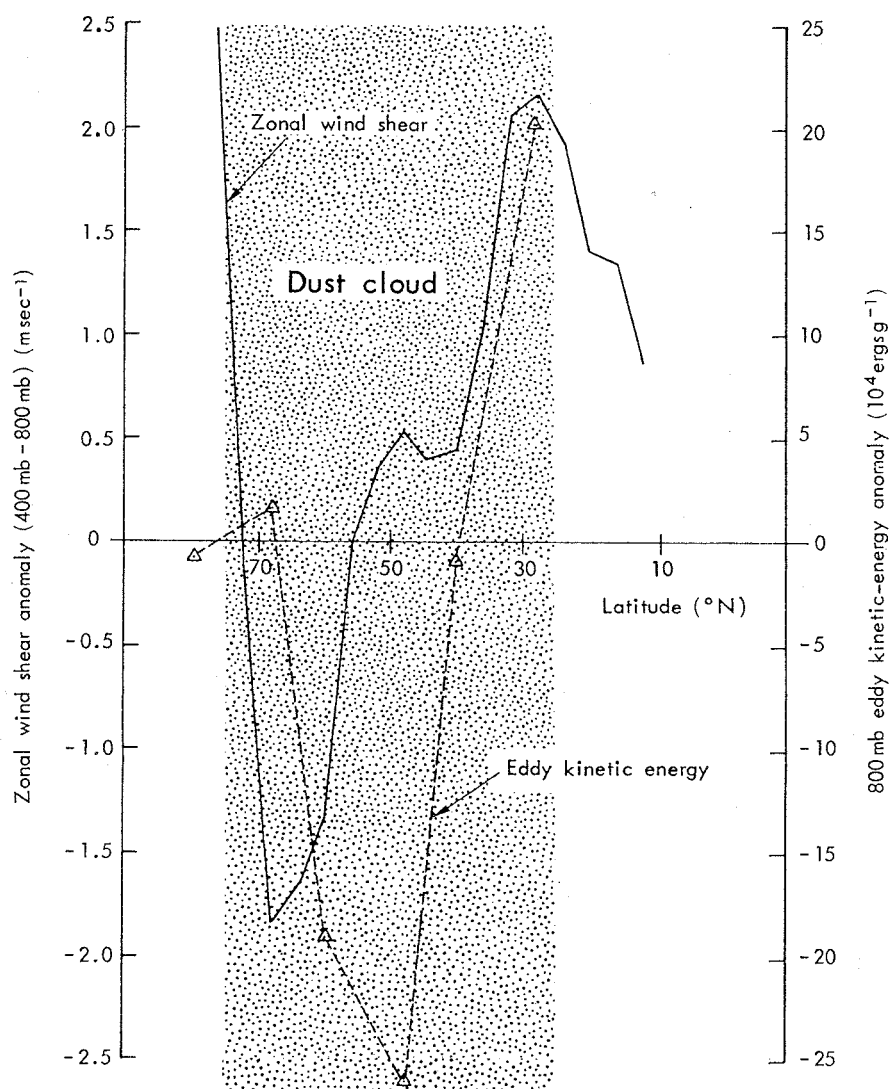


Fig. 11—Measures of baroclinic instability anomalies

IV. DISCUSSION

The results presented in the previous section raise some interesting questions that cannot be answered by a short 60-day simulation using a model with the present formulation. The results of the Black Cloud experiment (Kahle and Deirmendjian, 1973) suggest that the atmosphere has not yet reached a winter equilibrium state at the end of a 60-day simulation. There is no reason to believe that this experiment differs from the Black Cloud in that respect. Perhaps more significant to this experiment, which purports to represent conditions following a cataclysmic event, is the question of the model's ability to respond to events created by the perturbing influence and its ability to propagate these responses through the annual cycle and to other latitudes. The restrictions placed in the present model on the lower boundary conditions over both ocean and land surfaces represent a serious impediment to the model's ability to respond. Even by relaxing the restrictions on the lower boundary by specifying seasonally varying surface conditions, the model at best would be asked to respond to a previous "climate" not necessarily similar to the one the experiment attempts to produce. This experiment is a good example of some of these problems.

The presence of the dust cloud has resulted in decreasing temperatures over the land. One can reasonably assume that this would result in a southward extension of the snow field. The increase in the surface albedo produced by the snow covering would further reduce the solar radiation absorbed at the ground. At the present time the surface albedo is specified for each grid point and held constant in time. Clearly, a variable surface condition must be permitted in the basic model in order to realize the full impact on the atmosphere of perturbations like the stratospheric dust cloud.

Once having produced an abnormal southward extension of the snow field, it may be maintained for a longer period of time through spring and perhaps summer. Normally the surface near 45° latitude receives about 300 ly day^{-1} in spring and 500 ly day^{-1} in summer. A debris cloud persistent through the spring and summer seasons would reduce these amounts to approximately 180 ly day^{-1} and 300 ly day^{-1} ; a substantial loss of energy normally available to be used to melt snow and thaw the ground.

While the 39 percent loss of radiation to the atmosphere due to the dust cloud is in itself significant, the longer lasting high albedo of the persistent snow cover, a delayed snow melt, and a delayed thawing of the ground represent an additional loss of energy to the spring and summer atmosphere. For example, the albedo of old snow is 50 percent (Houghton, 1958) reducing the already depleted radiation absorbed by the ground in to 90 ly day^{-1} . Again, according to Houghton (1958), the loss of energy to the atmosphere in melting 5 cm of snow is 40 ly day^{-1} and thawing the ground in cloudy conditions is 80 ly day^{-1} . One must anticipate a greatly modified spring and summer followed by a winter with anomalous conditions substantially different from those shown by the present data.

In summary, the interesting results produced by this experiment suggest that further experimentation with perturbations of a similar nature is warranted. However, future experiments should be performed with a model capable of simulating the important feedback mechanisms, since we are looking for quasi-permanent changes that can be propagated in time and that are not diminished or removed as the dust cloud is removed. Some of the feedback mechanisms that the model should be able to simulate have been enumerated in the preceding paragraphs. One that

has not been listed and that should not be overlooked is the need to include a truly interactive ocean. As the land cools in response to the decreased solar radiation so should the ocean. Plans to include an ocean model are currently underway (Alexander, 1973).

Finally, in addition to the improved model but equally important, is the need to improve our understanding of the physical processes that are ultimately responsible for the attenuation of the solar radiation and modification of the precipitation. The effects of aerosols on solar radiation need further research if we are to improve the first-order estimates of the attenuation used in this experiment. Similarly, the effect of an increase of ice nuclei needs to be clarified. Regardless of the quality of the model and its integration, if we are not confident in our understanding of these processes, the interpretation of the results of any experiment will remain in doubt.

REFERENCES

- Alexander, R. C., 1973: *Ocean Circulation and Temperature Prediction Model: I. The Pacific*. The Rand Corporation, R-1296-ARPA.
- Batten, E. S., 1966: *The Effects of Nuclear War on the Weather and Climate*. The Rand Corporation, RM-4989-TAB.
- Deirmendjian, D., 1971: *Global Turbidity Studies: I. Volcanic Dust Effects—A Critical Survey*. The Rand Corporation, R-886-ARPA. See also "On Volcanic and Other Turbidity Anomalies" *Adv. Geoph.*, 16, 267-296 (1973).
- Deirmendjian, D., 1973: Unpublished memorandum.
- Gates, W. L., E. S. Batten, A. B. Kahle, and A. B. Nelson, 1971: *A Documentation of the Mintz-Arakawa Two-Level Atmospheric General Circulation Model*. The Rand Corporation, R-877-ARPA.
- Gates, W. L., 1972: *The January Global Climate Simulated by the Two-Level Mintz-Arakawa Model: A Comparison with Observation*. The Rand Corporation, R-1005-ARPA.
- Houghton, D. M., 1958: Heat Sources and Sinks at the Earth's Surface. *Meteorol. Mag.*, 87, 132-143.
- Humphreys, W. J., 1940: *Physics of the Air*, New York and London, McGraw-Hill.
- Kahle, A. B., and D. Deirmendjian, 1973: *The Black Cloud Experiment*. The Rand Corporation, R-1263-ARPA.
- Mason, B. J., 1960: "Ice-Nucleating Properties of Clay Minerals and Stony Meteorites." *Quart. J. Roy. Meteorol. Soc.*, 86, No. 370 pp. 552-556.
- Menzel, Donald H., 1953: On the Causes of the Ice Ages, Chapter 7, *Climatic Change*. Harlow Shapley (Ed.), Harvard University Press, Cambridge, Mass.
- SCEP, 1970: *Man's Impact on the Environment. Report of the Study of Critical Environmental Problems*. MIT Press, Cambridge, 319 pp.
- SMIC, 1971. *Inadvertent Climate Modification. Report of the Study of Man's Impact on the Environment (SMIC)*. MIT Press, 308 pp.
- Spar, Jerome, 1973: Some Effects of Surface Anomalies in a Global General Circulation Model. *Monthly Weather Rev.*, 101, 2, 91-100.
- Stonier, T., 1963: *Nuclear Disaster*. Meridian Books (M154), The World Publishing Company, Cleveland and New York.
- Warshaw, M., and R. R. Rapp, 1973: An Experiment on the Sensitivity of a Global Circulation Model. *J. Appl. Meteorol.*, 12, 1, 43-49.
- Washington, Warren M., 1971: On the Possible Use of Global Atmospheric Models for the Study of Air and Thermal Pollution. *Man's Impact on the Climate*, W. H. Matthews, et al. (Eds.), Cambridge, Mass., The MIT Press, 265-276.
- Washington, Warren M., 1972: Numerical Climatic-Change Experiments: The Effect of Man's Production of Thermal Energy. *J. Appl. Meteorol.*, 11, 5, 768-771.
- Wexler, H., 1953: *Radiation Balance of the Earth as a Factor in Climatic Change*, Chapter 5, *Climatic Change*, Harlow Shapley (Ed.), Harvard University Press, Cambridge, Mass.
- Wexler, H., 1956: Variations in Insolation, General Circulation and Climate. *Tellus*, 8, 4, 480-494.