Internally and Externally Caused Climate Change

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ABSTRACT

A numerical climate model is used to simulate climate change forced only by random fluctuations of the atmospheric heat transport. This short-term natural variability of the atmosphere is shown to be a possible "cause" not only of the variability of the annual world average temperature about its mean, but also long-term excursions from the mean.

Various external causes of climate change are also tested with the model and the results compared with observations for the past 100 years. Volcanic dust is shown to have been an important cause of climate change, while the effects of sunspot-related solar constant variation and anthropogenic forcing are not evident.

1. Introduction

Instrumental surface temperature records have been compiled for large portions of the globe for about the past 100 years (Mitchell, 1961; Budyko, 1969). They show that the Northern Hemisphere annual mean temperature has risen about 1°C from 1880 to about 1940 and has fallen about 0.5°C since then (Figs. 1–3). Various attempts to simulate this temperature record (Schneider and Mass, 1975; Pollack *et al.*, 1976; Bryson and Dittberner, 1976) have all focused on external causes, such as volcanic dust, solar constant variations and anthropogenic effects. It is possible, however, that even in the absence of any external forcing a unique climate may not exist. Climate change may be a natural internal feature of the land-ocean-ice-atmosphere (climate) system.

The theory of internal causation of climate change has been developed by Lorenz (1968, 1970, 1976). He suggested that climate change might just be the natural variations due to the complex nonlinear interactions among the various components of the climate system. One of these components is the meridional heat flux accomplished in midlatitudes primarily by baroclinic eddies. VonderHaar and Oort (1973) provide data that show that the standard deviation of the annual average of the atmospheric energy flux is about 9.9% of the mean flux. This variable heat flux results in variable storage and release of heat in various locations in the climate system, such as the land and ocean surface, and the snow and ice covers. These result in changing annual mean temperatures which might be interpreted as climate change, without any external forcing. Hasselmann (1976), Frankignoul and Hasselmann (1977), Frankignoul (1977) and Lemke (1977) have also recently performed theoretical studies of stochastic forcing of climate.

In this study a seasonal, zonally averaged, vertically averaged, highly parameterized numerical model is forced with a randomly perturbed eddy heat flux to test its sensitivity to internal forcing. The magnitude

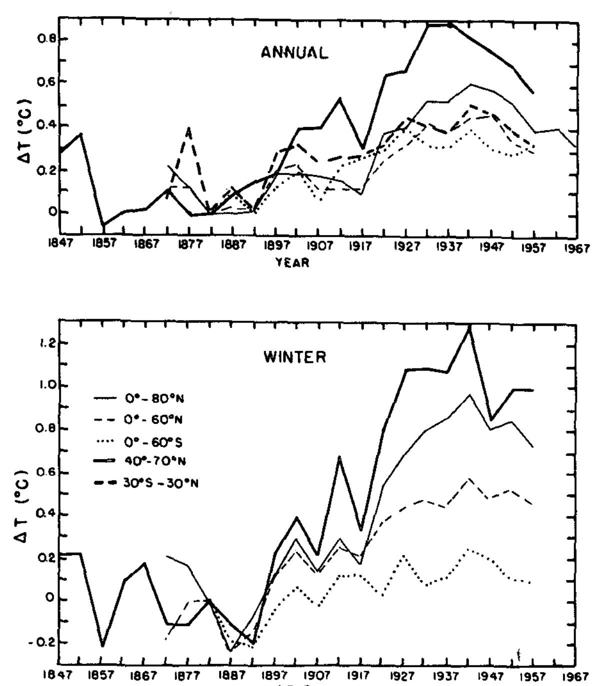

FIG. 1. Five-year average temperatures by latitude bands, from Mitchell (1961). The 0–80°N annual record is updated by Reitan (1974). The centers of the 5-year averaging periods are indicated on the abscissa.

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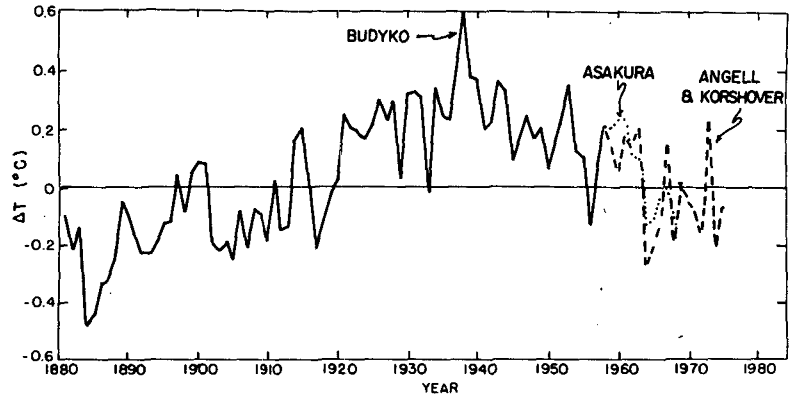

FIG. 2. Annual mean temperature of the Northern Hemisphere for 1881–1975, from Budyko (1969), Asakura (Gates and Mintz, 1975) and Angell and Korshover (1977).

of the response is then compared to that from various plausible external forces. In this way the actual sensitivity of the climate system to various forcings can be investigated. This sensitivity cannot be determined precisely from observations. The temperature drop following the eruption of Mt. Agung in Bali in 1963 (Angell and Korshover, 1977) surely must have been related to the eruption. But how much of this change was due to the eruption, and how much was due to other causes, including natural variability?

A numerical model based on the model of Sellers (1973, 1974) was used to test these theories of climate change. Although the model was formulated to calculate time-dependent climate change, Sellers only used it to calculate equilibrium states resulting from different external conditions. An indication of the time-dependent nature of the model is given in Fig. 9 of Sellers (1973), but Sellers (1974) did his best to eliminate this feature from his studies. The model, then, seemed ideally designed for time-dependent simulation, and had not been used for this purpose. Several changes were made in Sellers' model to correct minor errors, but no new parameterizations were introduced. Robock (1978) gives a complete description of the model, the changes made, its ability to reproduce the observed climate, and its sensitivity to parameter and parameterization changes.

The model simulates the observed seasonal cycles of temperature, radiation and horizontal heat fluxes quite well with one exception. Due to inaccurate snow and ice parameterizations, the ice areas are too large, and the snow line has a seasonal amplitude that is too small. In the polar regions, therefore, the surface temperatures and seasonal cycles are slightly different from the observations. Due to the extreme sensitivity of the model to this one parameter, however, this results in an ice (snow)-albedo feedback which is too large, making the model too sensitive to external forcings. The experimental results reported in the next section should therefore be regarded as qualitatively correct, but with the quantitative sensitivity of the model to the various forcings exaggerated.

2. The experiments

a. *Internal causes*

The model in the balanced state exactly reproduces the seasonal cycle of all the variables year after year

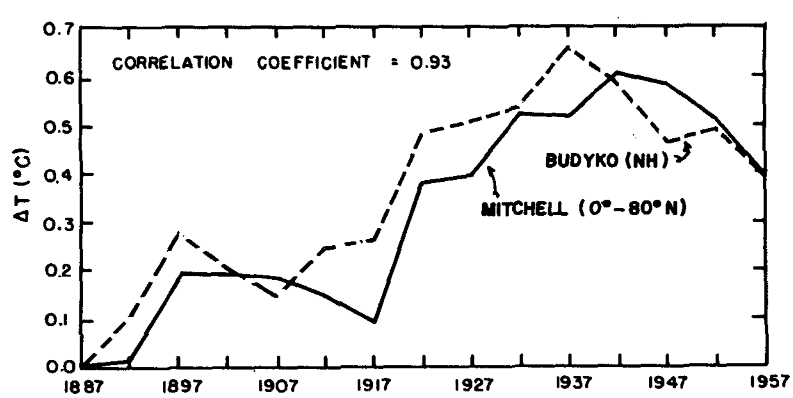

FIG. 3. Budyko-Mitchell correlation of 5-year average Northern Hemisphere temperature record.

TABLE 1. Results of 100-year atmospheric eddy perturbation runs (all temperatures in kelvins).

Run no.	1	2	3	4	5	6	Average of 1–6	Observations	7	8	9
N_0†	19		3		11				19	19	19
Note:		Starting from end of no. 1		Starting from end of no. 3		Starting from end of no. 5			Sellers' infrared	Zero order Markov	SD of flux = 0.2°C
Standard deviation of:											
Atmospheric energy flux (% of total)	7.35	7.73	8.08	8.28	6.86	7.99	7.72	9.9	7.37	3.73	3.53
World T	0.152	0.260	0.228	0.207	0.171	0.191	0.202		0.137	0.074	0.074
World T*	0.152	0.252	0.153	0.203	0.168	0.191	0.187		0.137	0.072	0.071
NH T	0.271	0.424	0.336	0.352	0.384	0.361	0.355	0.22	0.249	0.125	0.120
NH T*	0.261	0.423	0.273	0.350	0.379	0.361	0.341	0.18	0.235	0.124	0.119
SH T	0.200	0.292	0.264	0.245	0.186	0.179	0.228		0.174	0.100	0.108
SH T*	0.178	0.272	0.222	0.211	0.185	0.174	0.207		0.160	0.087	0.089

† N_0 is initial number for random number generator.
* With linear trend removed.

and produces a constant annual average temperature. In order to simulate the natural variability observed in the atmosphere, random perturbations of the eddy flux of sensible heat are introduced in the model. The resulting temperature record is then compared to observations, to see whether the resulting variations are of a magnitude that could be interpreted as climate change.

Without perturbations, the eddy sensible heat flux can be expressed as

$$\overline{v'T'}=-K\frac{\partial T}{\partial y},$$

where

$$K=C\overline{\overline{\left|\frac{\partial T}{\partial y}\right|}},$$

the double bar indicating a 1–2–1 smoothing. With perturbations, the flux is expressed as

$$\overline{v'T'}=-K\frac{\partial T}{\partial y}+R,$$

where

$$R'=\hat{B}_l\left(\overline{\overline{\frac{\partial T}{\partial y}}}\right)^2,$$

l = latitude index,

$$\hat{B}_l=70^{0.5}(B_{l-2}+4B_{l-1}+6B_l+4B_{l+1}+B_{l+2}).$$

Each B is a random normally distributed number with mean zero and standard deviation equal to a given percentage of C. For these experiments $0.4C$ was chosen because it gave the largest magnitude for the standard deviation of the atmospheric eddy heat flux without numerical instability for a first-order Markov process. The 1–4–6–4–1 smoothing applied to $\hat{B}$ simulates the observed latitudinal extent of baroclinic eddies. The $70^{0.5}$ factor keeps the expected value of the standard deviation of $\hat{B}$ the same as that of B. Making the perturbations proportional to the temperature gradient squared makes them strongest in the midlatitudes, and in the winter, both in agreement with the observations of Oort and VonderHaar (1976). For a zero-order Markov process, $R=R'$. For a first-order Markov process, $R_n=\hat{\alpha}R_{n-1}+R'$, where n refers to the time step. Since the model time step is about 15 days, and McGuirk and Reiter (1976) found flux oscillations with periods of about 24 days, they were simulated as a first-order Markov process. The constant $\hat{\alpha}$ was chosen to be 0.5. Runs using a zero-order Markov process and the same set of random perturbations gave almost the same temperature perturbations, but with a smaller magnitude.

Three 100-year runs were made with three different sets of random numbers, starting from balanced initial conditions. In these runs, the eddy perturbations were simulated as a first-order Markov process, with the standard deviation of $B=0.4C$ and $\hat{\alpha}=0.5$. Each of these runs was then extended for another 100 years. These additional runs may be looked at as independent 100 year runs, or extensions of the initial runs. Three other runs were done, using the same set of random numbers as one of the first 100-year runs, to test the sensitivity to parameterizations. In one of these, the perturbations were treated as a zero-order Markov process. In another, the standard deviation of B was set equal to $0.2C$. In the final one, Sellers' infrared scheme was used, to see the response of a system with a different (lower) sensitivity. These runs are summarized in Table 1, and the resulting world, Northern (NH) and Southern Hemisphere (SH) temperature records are shown in Figs. 4–7.

For each run, the standard deviation of the annual

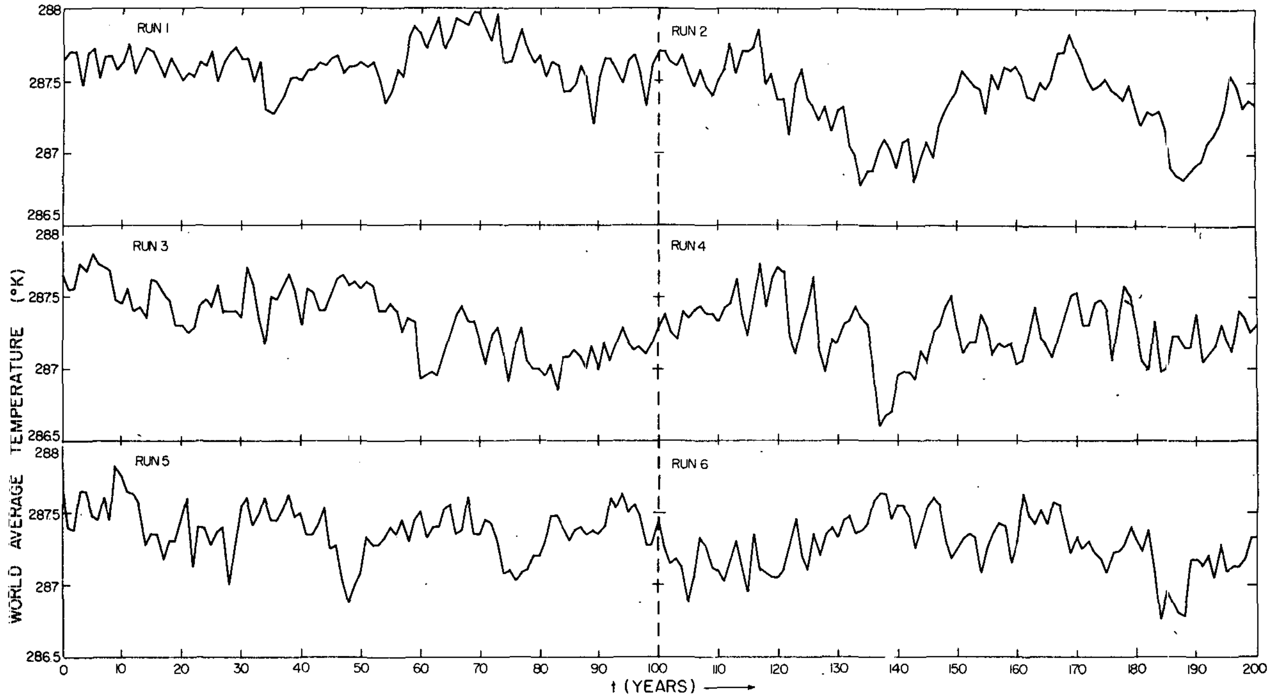

FIG. 4. World average temperature from internal forcing runs (1–6).

average atmospheric energy flux was calculated for comparison to the data of VonderHaar and Oort (1973). They found an average standard deviation of 9.9% for the portion of the globe that was covered by their data. They originally attributed all of this variation to observational error, but now think that almost all of it is due to actual atmospheric variability (Oort, 1977). The computed standard deviations are shown

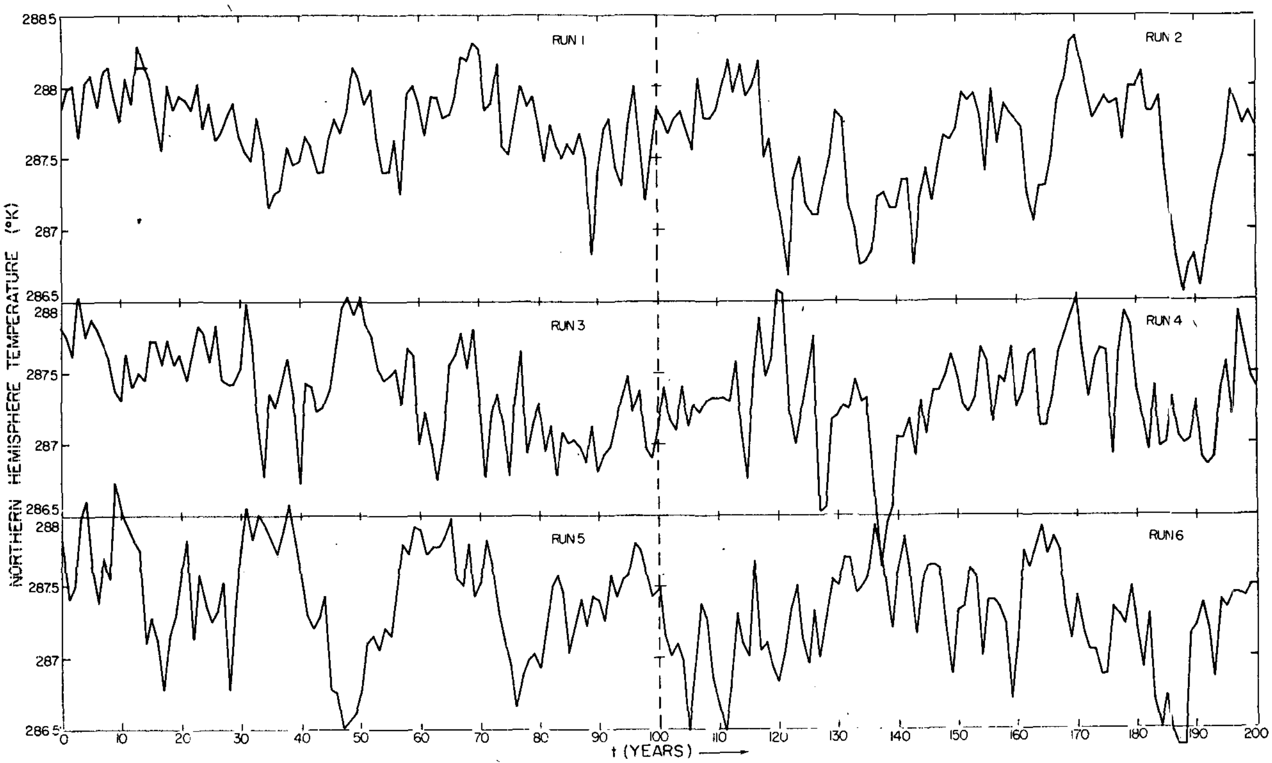

FIG. 5. Northern Hemisphere temperature from internal forcing runs (1–6).

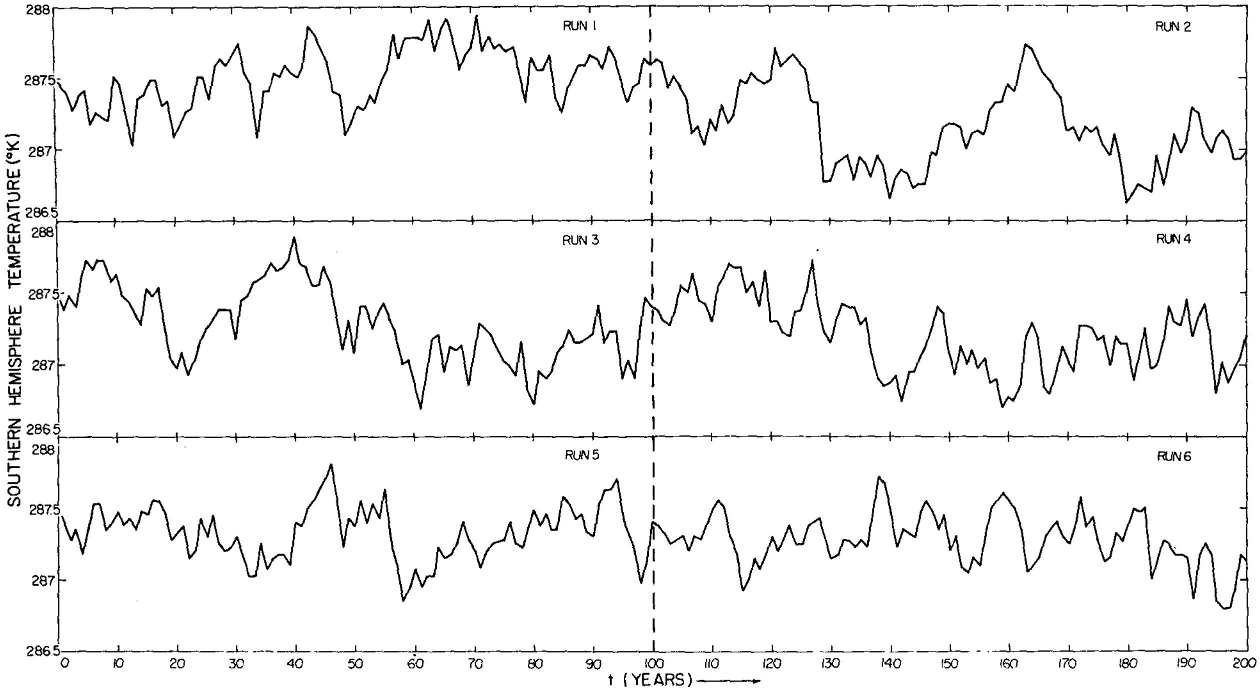

FIG. 6. Southern Hemisphere temperature from internal forcing runs (1–6).

in Table 1. The average standard deviation of the six similar runs is about 7.7%.

For each run, the standard deviations of the resulting annual average world, NH and SH temperature fields were also calculated and are shown in Table 1. Because some of the fields had a linear trend which added to the standard deviation, this linear trend was subtracted out, and the standard deviations were recalculated. They are also shown in Table 1. These results are compared to the standard deviation of the Budyko-Asakura NH temperature record, which is 0.22 K for the raw data and 0.18 K with the linear trend removed.

The six similar runs produced NH standard deviations larger than observations, with a mean of about 0.35 K. The zero-order Markov run and the run with half the standard deviation of the forcing both produced standard deviations of the atmospheric energy flux and the temperature that were about half those of the standard run. The run using Sellers' infrared scheme had virtually the same flux deviation, but the standard deviation of the temperature was about 10% lower.

These results are not incompatible with the conclusion that the variability of the annual mean temperature can be explained by the forcing due to random unstable atmospheric eddies. If the strength of the forcing were lowered to a standard deviation of the flux of about 4.4%, then this model would give NH temperature standard deviations equal to the observations. Changes in the model might, however, lower the sensitivity and allow a higher flux deviation to produce the same temperature deviation. As shown by Robock (1978), the model itself may be too sensitive. The run with Sellers' infrared scheme shows that if the model were less sensitive, the same flux deviation would produce a lower temperature deviation. Thus a model version

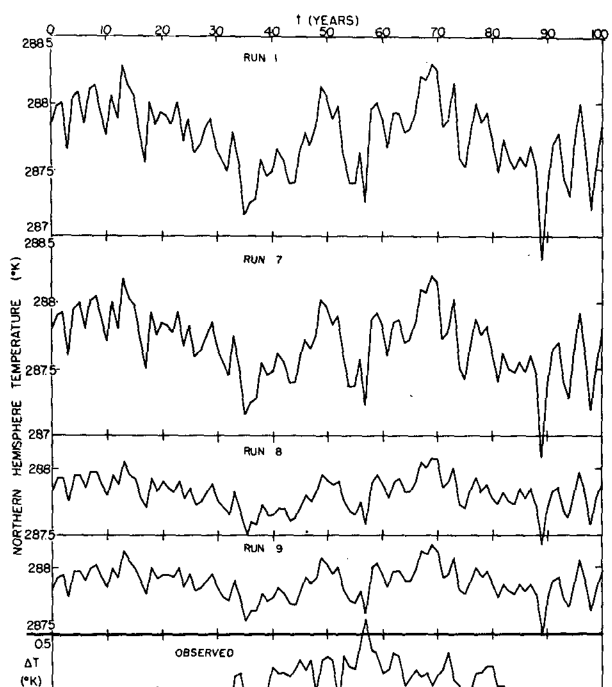

FIG. 7. Northern Hemisphere temperature from internal forcing runs (1, 7–9) compared to Budyko-Asakura data.

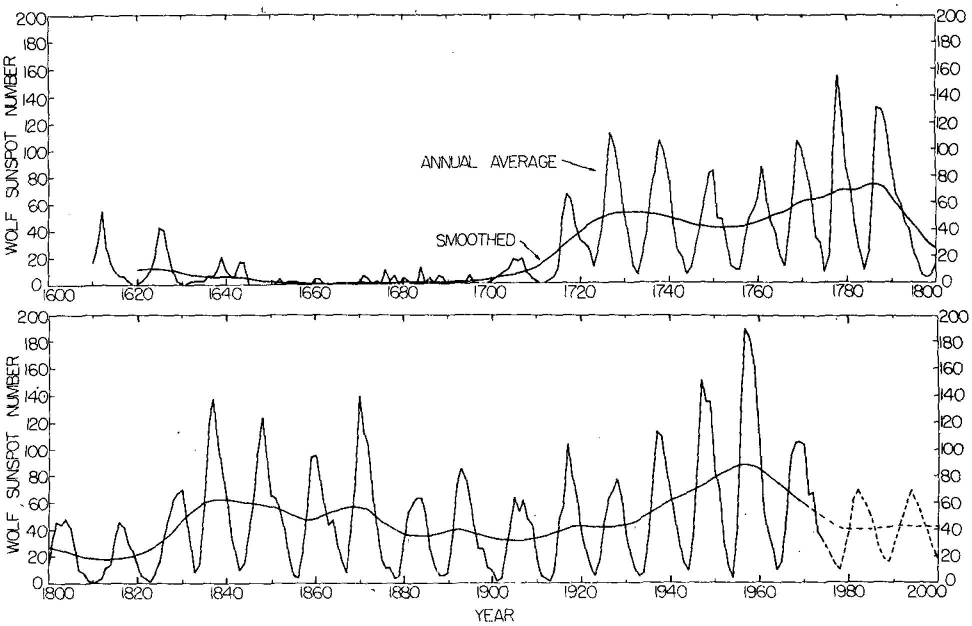

FIG. 8. The Wolf relative sunspot number from 1610–2001. Shown are both annual average values and values with the 11-year cycle smoothed out, according to a suggestion by Eddy (1976) that climate may be related to the overall envelope of the sunspot number.

which is less sensitive to solar constant changes is also less sensitive to eddy flux perturbations.

The temperature graphs from these runs show that not only is "noise" about a mean produced by the random eddy perturbations but also large excursions of the temperature. Even if the temperature response is scaled down so that the standard deviations are the same as the observations, NH temperature excursions of 0.5 K occur in one year. The temperature may remain relatively constant for up to 10 years and then shift to a value 0.5 K different and stay at that value for several years. Rapid shifts year after year also occur. Long-term trends are also produced. In fact, with no external forcing, internal variations of the observed magnitude produce NH temperature fluctuations as large as those observed for the past 100 years!

b. External causes

The model was also used to test the following possible external causes of climate change: volcanic dust, sunspot-related solar forcing, and anthropogenic carbon dioxide, aerosols and heat. To test sunspots and volcanic dust, the model was run for 380 years of simulated time starting in 1621 with the appropriate forcing applied, and the results were compared to the data of Mitchell and Budyko (Figs. 1 and 2). For anthropogenic forcing the experiments were instead run for 160 years starting in 1841, since no anthropogenic forcing occurred before then.

Sunspots have been observed since Galileo invented the telescope in 1610. These observations are shown in Fig. 8. Kondratyev and Nikolsky (1970) presented the following observed relationship between solar constant (Q) and Wolf sunspot number (N):

$$Q=1327.98+7.68N^{0.5}-0.42N \text{ [W m}^{-2}\text{]}. \quad (1)$$

Their measurements included effects of atmospheric nuclear testing and the eruption of Agung and so are open to serious question. Therefore, the following hypothetical simple relationships were also tested:

$$Q=A+BN, \quad (2)$$

$$Q=A+BN^{0.5}, \quad (3)$$

with $A=1343.3$ W m^{-2}, $B=0.21$ in (2) and $B=1.40$ in (3) in order to make the solar constant equal to 1353.8 (its current value) during the past century when the average N was $\sim$50. Not knowing whether sunspots actually increase or decrease Q, a run was also tried with $A=1364.3$ and $B=-0.21$ in (2). The magnitude of the N effect on Q was chosen so as to give a large enough signal in the temperature response to notice, but not so large as to make the model unstable. The linear relationship (2) was run for three different sets of N—monthly average, annual average and with the sunspot cycle smoothed out (see Fig. 8) according to the suggestion of Eddy (1976) that the solar constant is a function of the envelope of the sunspot number. Since the smoothed data set gave the only reasonable output, because the 11-year cycles produced by the other data are not observed, it was used for relationship (3) and for (2) with B negative.

The volcanic dust theory was tested in two runs, one using the data of Lamb and one using the data of Mitchell (Fig. 9). In both cases the volcanic dust

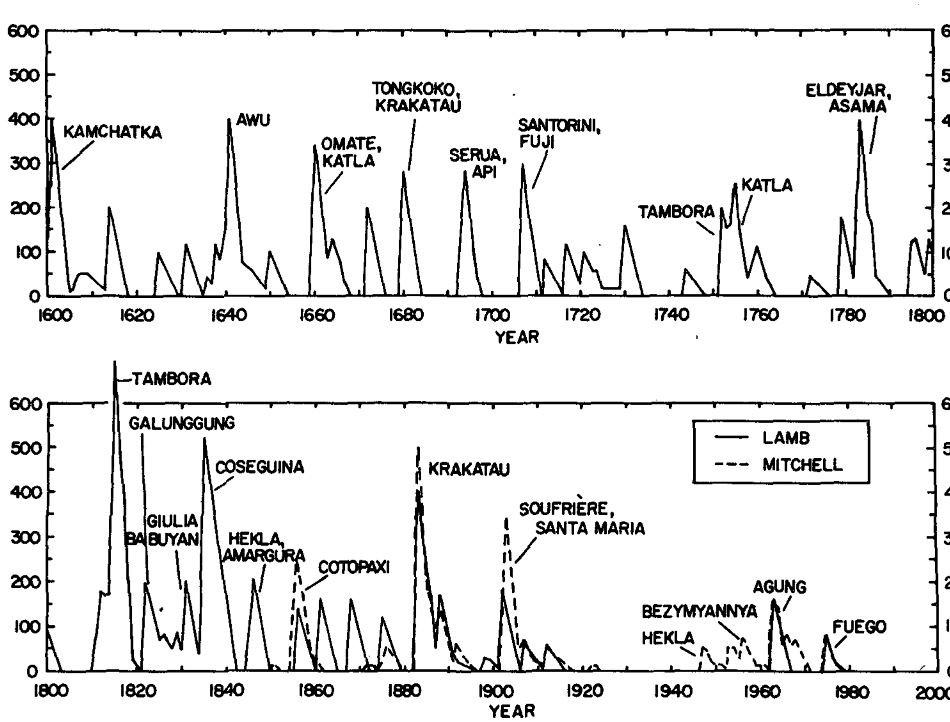

FIG. 9. Volcanic dust veil index (DVI) for Northern Hemisphere, from Lamb (1970) and Mitchell (1970).

was simulated by reducing the solar constant by an amount proportional to the dust veil index (DVI), calibrated by assuming the Agung dust (DVI=160) produced a 0.5% decrease in Q, following Schneider and Mass (1975). In both cases, the non-volcanic Q was set to 1357.3 at the beginning of the run to make the average $Q \approx 1353.8$ and avoid any trend associated with imbalanced initial conditions.

Anthropogenic effects were simulated in three runs. Carbon dioxide was changed according to Broecker (1975) (Fig. 10) in the first one. In the second one, aerosols were simulated by increasing the optical depth by an amount proportional to the excess anthropogenic CO_2 with the distribution given by Kellogg (1977). It was calibrated by assuming that in the most polluted grid area, the excess aerosol was equal to 20% of the natural level in 1972. In the third run, heat was simulated with the same time dependence as CO_2 and aerosols, with the same latitudinal distribution as aerosols, but with the entire source on land and calibrated by assuming the total anthropogenic heat input to be 8×10^{12} W in 1972. The 12 runs described above are listed in Table 2.

The model results were plotted against the data for all nine of Mitchell's sets of 5-year averaged temperatures, and annual and 5-year averaged Budyko and Asakura temperatures. It is not possible to present 11 graphs for each run, so representative ones are presented for some runs.

Correlation coefficients between the model output and the data were also calculated. These are shown in Tables 2 and 3 for all the runs. This method of comparison was used because it does not depend on the relative magnitudes of the model output and the data. Because the sensitivity of the model is questionable, as discussed above, it would not be expected to give perfect quantitative responses to different climate forcings. Still, reasonable responses would be expected, since all the forcings used, except those of Eqs. (2) and (3), are based on the observed magnitudes of the forcing.

TABLE 2. List of simulation runs and correlations with Budyko-Asakura data.

Run no.	Theory	Data*	A	B	Correlation coefficients of results with Budyko-Asakura data: 5-year average	1-year average
1	$K+N$ (1)	M			0.29	0.12
2	$K+N$ (1)	A			0.32	0.05
3	(2)	M	1343.3	0.21	0.18	0.10
4	(2)	A	1343.3	0.21	0.17	0.10
5	(2)	S	1343.3	0.21	0.18	0.07
6	(3)	S	1343.3	1.40	0.20	0.08
7	(2)	S	1364.3	−0.21	−0.21	−0.10
8	Volcanoes	Lamb			0.88	0.75
9	Volcanoes	Mitchell			0.92	0.77
10	Anthropogenic	CO_2			0.61	0.42
11	Anthropogenic	Aerosols			−0.63	−0.44
12	Anthropogenic	Heat			0.63	0.44

* M, monthly, A; annual; S, smoothed.

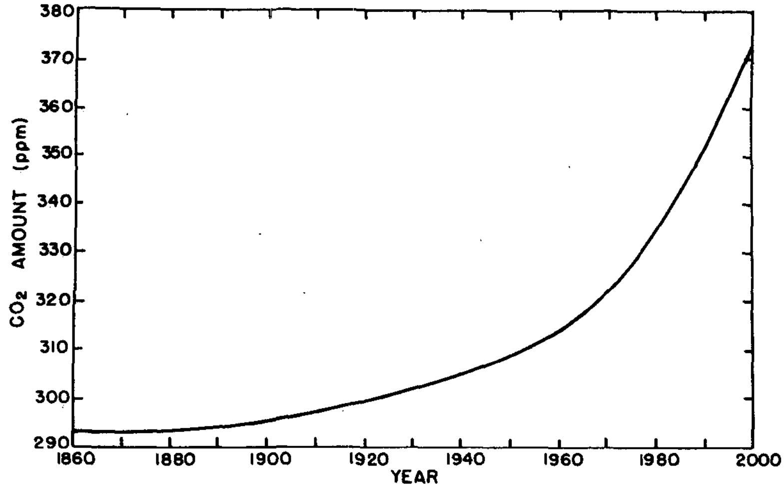

FIG. 10. Atmospheric CO_2 content, from Broecker (1975). It was constant at 293 ppm before 1880.

1) SOLAR FORCING

None of the solar forcing runs produced results resembling the observational data. The correlation coefficients for all the data sets were low. There was little difference in the results between using monthly or annually averaged sunspot data (see Tables 2 and 3, and Fig. 11). The thermal inertia of the model was high enough to integrate the variable monthly forcing. Using smoothed data also made no difference in the resulting correlations with the observations, but gave different looking temperature series. The monthly and anually averaged runs gave results with very evident sunspot cycles, which were missing from the observed data. Run 6, using formula (3), gave results almost identical to the other runs. Run 7, with a negative effect of sunspots on the solar constant, also gave very low correlations with the observed data. Solar forcing alone, therefore, cannot explain the past observed climate change.

2) VOLCANIC DUST

Both volcanic dust runs produced results resembling the observations. Fig. 12 compares the 0–80°N annual data of Mitchell with both results, and Fig. 13 compares the results of Run 9 with Budyko's data. Although the Mitchell run produced slightly lower correlations than the Lamb run (Run 8), the results include the temperature drop after the 1940's, forced by volcanoes that Lamb did not include.

The best results are those for the entire Northern Hemisphere using the results of Budyko and Asakura, and for 0–80°N from Mitchell. This is understandable, since the volcanic dust data were NH average data. Forcing with the correct latitudinal dependence would probably give equally good results for all the fields. The worst results are for 40–70°N which presumably is the best of the data records, with the longest record and the highest station density. The worst agreement is for the period before 1880, where the model results

TABLE 3. Correlation coefficients of 5-year average results of simulation runs with Mitchell data. W = winter, A = annual.

Run	0–80°N		0–60°N		0–60°S		40–70°N		30°N–30°S
no.	W	A	W	A	W	A	W	A	A
1	0.19	0.32	−0.06	0.21	0.05	0.09	−0.12	−0.21	0.22
2	0.22	0.35	−0.03	0.24	0.07	0.11	−0.11	−0.19	0.24
3	0.19	0.25	0.02	0.14	0.05	0.09	−0.08	−0.18	0.10
4	0.19	0.25	0.02	0.14	0.05	0.09	−0.09	−0.18	0.10
5	0.21	0.25	0.06	0.17	0.06	0.08	−0.08	−0.18	0.08
6	0.22	0.26	0.06	0.18	0.07	0.10	−0.06	−0.16	0.10
7	−0.26	−0.27	−0.11	−0.21	−0.09	−0.13	0.03	0.14	−0.12
8	0.95	0.89	0.95	0.89	0.81	0.86	0.82	0.76	0.82
9	0.94	0.90	0.86	0.88	0.77	0.80	0.72	0.67	0.77
10	0.84	0.66	0.82	0.78	0.61	0.71	0.82	0.76	0.67
11	−0.86	−0.67	−0.83	−0.80	−0.61	−0.71	−0.84	−0.78	−0.68
12	0.86	0.67	0.83	0.80	0.61	0.71	0.84	0.78	0.68

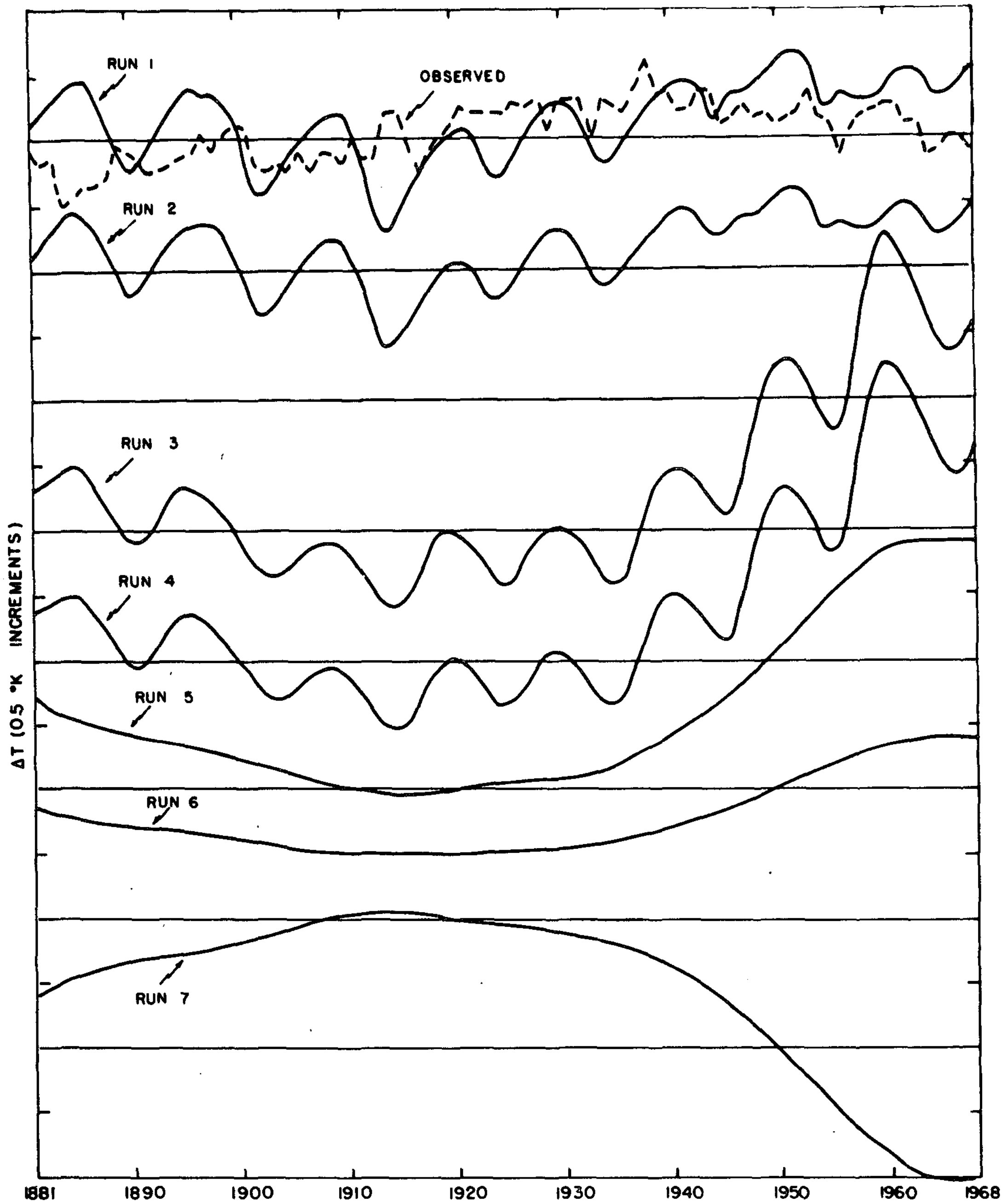

Fig. 11. Results of solar forcing runs (1–7) compared to Budyko-Asakura annual average data for 1881–1968.

have the temperature increasing sharply and the data show the temperature to be relatively constant. This is probably because the data are in error. There are very few stations used for this portion of the data, and Mitchell admits that they may not be enough to be representative (personal communication). Furthermore, two other available records (Gates and Mintz, 1975) show a rising temperature during this period, closely resembling the model results and not Mitchell's data. Without this discrepancy, the 40–70°N results would be as good as the others.

Volcanic dust, therefore, seems to have been an important cause of climate change during the past 100 years. The general shape of the observations is very well simulated, but not the details. This is due to several causes. First, there are inaccuracies in the model, in the past temperature record and in the volcanic data. The most serious of these is that the volcanic data are averaged for the entire NH, and Cadle *et al.* (1976) have shown that volcanic dust in the stratosphere is confined to smaller latitudinal regions. Better, latitude-dependent volcanic forcing would probably produce

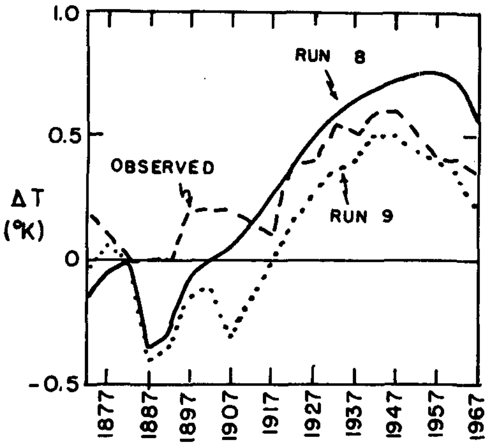

FIG. 12. Results of volcanic dust simulation runs (8–9) compared to Mitchell-Reitan 0–80°N annual 5-year average data for 1870–1969.

equally good agreement in all latitude bands. Second, the observational data are much noisier than the model output. This noise can be explained as due to the natural variability of the system. Also, anthropogenic effects may have been important. These are discussed in the next section.

3) Anthropogenic effects

Three runs were made testing anthropogenic effects of CO_2, aerosols and heat. The 0–80°N results are shown in Fig. 14. The correlation coefficients with the observations are shown in Tables 2 and 3, and the resulting temperature changes are shown in Table 4 for three different years.

Both CO_2 and heat produced warming, with the CO_2 effect being almost an order of magnitude larger than the heat effect. Aerosols produced cooling, but the magnitude, and even the sign of this effect, are open to much question due to our incomplete knowledge of the physical and chemical processes involved.

CO_2 produced a slightly larger effect in the NH than in the SH, due to the larger percentage of land in the NH. This results in less thermal inertia and a larger snow-albedo feedback, both contributing to the larger sensitivity. Both aerosols and heat produced an even larger hemispheric difference, due to the additional fact that their forcing is much stronger in the NH. The response in the region 40–70°N is even larger than the NH response. This is because this region has a high percentage of land and it is near the pole, which is more sensitive to climate change than the hemispheric average. This geographic distribution of response is discussed later. It is also in agreement with Mitchell's data which show a larger climate change in this region than in the whole NH.

TABLE 4. Results of anthropogenic simulation runs. Annual average temperature change ΔT (°C) from 1880 values.

	World	NH	SH	40–70°N
1960				
CO_2	+0.119	+0.130	+0.110	+0.173
Aerosols	−0.112	−0.137	−0.085	−0.186
Heat	+0.014	+0.019	+0.010	+0.026
1980				
CO_2	+0.221	+0.238	+0.205	+0.312
Aerosols	−0.207	−0.256	−0.157	−0.345
Heat	+0.026	+0.035	+0.019	+0.050
2000				
CO_2	+0.423	+0.442	+0.404	+0.572
Aerosols	−0.408	−0.507	−0.309	−0.687
Heat	+0.055	+0.072	+0.037	+0.106

One could sum the anthropogenic effects for each region, which would show almost no effect in the NH and warming in the SH. Drawing conclusions from this exercise would not be meaningful, however, due to our lack of understanding of the aerosol effect.

All the effects almost double every 20 years. They are not of sufficient magnitude to have much effect on the observational records, which end about 1960, but may have a measurable effect in the near future.

The relative magnitudes of the effects may change in the future due to changing human pollution policies. Restrictions on particulate pollution and anticipated measures against sulfate aerosols will lessen the effects

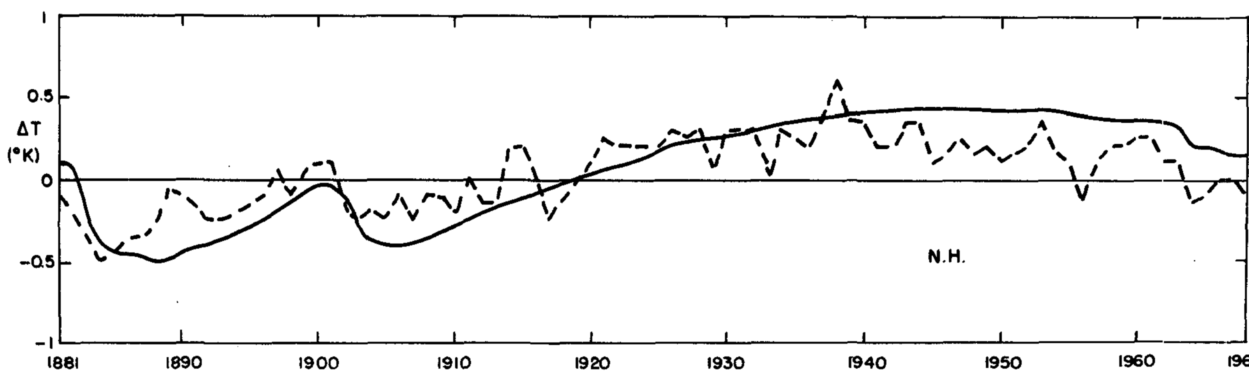

FIG. 13. Results of Mitchell volcanic dust simulation run (9) (solid curve) compared with observations of Budyko-Asakura (dashed curve).

of industrial aerosols. Increased dependence on nuclear energy would increase the ratio of heat to CO_2 effect, while an increased dependence on coal would not.

It can be seen in Tables 2 and 3 that the anthropogenic runs produce large positive and negative correlations with the observations that might be interpreted as significant. In fact, the aerosol and heat runs produce identical values with opposite signs due to the almost identical latitudinal and temporal distribution of their forcings, but opposite effects. The reason for the high correlations is that the observations have an upward linear trend, and the smooth rising or falling temperatures produced by the anthropogenic forcings produce high correlations. Because the magnitudes of the effects are small, and may cancel, it cannot be concluded that these high correlations show that man has produced climate change.

c. *Geographical sensitivity*

Certain regions of the globe are more sensitive to climate change than others, both in observations and in the model results. This is due mainly to thermal inertia differences for different surface composition, namely, that the oceans have a much larger thermal inertia than land or ice. Snow has virtually the same thermal inertia as land or ice and so the snow-albedo feedback does not affect the sensitivity through thermal inertia. However, the radiative effects of this feedback act to make regions where it is occurring more sensitive than other regions. To summarize, land and ice regions are more sensitive than ocean due to their lower thermal inertia. The additional effects of snow-albedo feedback make regions with a large portion of land even more sensitive. This feedback has a much smaller effect on ice because of the smaller albedo difference between ice and snow.

The above mechanisms work to make the NH more sensitive than the SH, and this was found to be the case in all the simulation experiments, both external and internal. These mechanisms also work to make the polar regions more sensitive than the tropics. Table 5 shows the latitudinal distribution of the temperature response from lowering the solar constant by 1%, after 500 years. The response is typical of all the other experiments, and shows the polar regions approximately twice as sensitive as the tropics. This response can also be seen in Mitchell's data (Fig. 1).

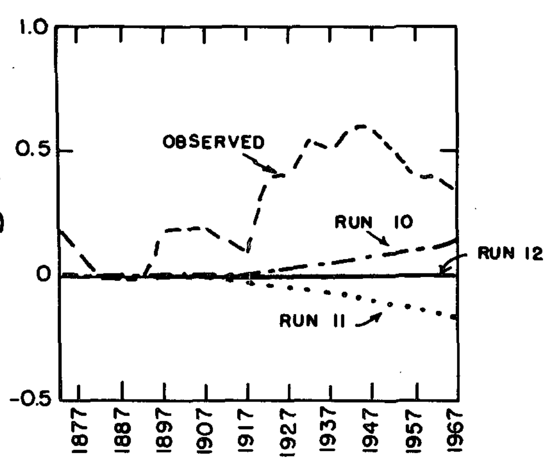

FIG. 14. Results of anthropogenic forcing simulation runs (10–12) compared to 0–80°N annual Mitchell-Reitan 5-year average data for 1870–1969.

TABLE 5. Latitudinal distribution of temperature response (°C) to lowering Q by 1%, after 500 years.

Latitude band	$\Delta \bar{T}_0$
80–90°N	−6.72
70–80°N	−6.87
60–70°N	−6.99
50–60°N	−6.56
40–50°N	−5.36
30–40°N	−4.49
20–30°N	−4.02
10–20°N	−3.82
0–10°N	−3.77
0–10°S	−3.77
10–20°S	−3.75
20–30°S	−3.86
30–40°S	−4.24
40–50°S	−4.84
50–60°S	−5.80
60–70°S	−6.12
70–80°S	−6.05
80–90°S	−5.80

3. Discussion and conclusions

The natural variability of the atmosphere, through random short-term variations in the dynamical fluxes, has been shown to produce unpredictable long-term variations in the climate. This result can be considered as a demonstration of the importance of internal causation of climate change. It can also be thought of as a test of the sensitivity of the climate system to baroclinic instability as a forcing mechanism, since this is not explicitly calculated in the unperturbed model.

The magnitude of the model response to internal forcing is evaluated by comparison with actual data and the model response to external forcing. Even if the model were half as sensitive as it is, internal forcing would still be important as compared to the observed temperature variability. Volcanic dust is the only external forcing that produces a model response significantly like the observations. In fact, results show that it is an important cause of climate change. Combined with internal forcing, it may explain the climate change of the past 100 years.

Globally forced climate change is amplified at the poles, especially in the Northern Hemisphere. The Northern Hemisphere is more sensitive than the Southern, and land areas are more sensitive than oceans.

Once improvements are made in the model, particularly in the ice and snow parameterizations, more experiments will be conducted to further test the above results. Runs will be made combining different forcings. Preliminary results indicate that they have a linearly additive effect, as even the "internal" forcing is actually externally imposed in the above experiments without a feedback on the forcing. In addition, the mechanism that produces long-term climate change from short-term random forcing will be investigated. Is heat storage in the ocean or anomalous snow and ice cover more important in producing this response?

A simple energy balance model has been used to investigate climate change. It is hoped that further investigations with this and other approaches will one day lead to a better understanding of the nature of climate change.

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