Dynamical Climatology

On modelling the effects of CO_2 on climate

by

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Summary

The sensitivity of the Meteorological Office's 5-layer atmospheric general circulation model to enhanced atmospheric CO_2 concentrations with both a uniform and a latitudinally varying increase in sea surface temperatures is assessed. The changes in atmospheric temperatures depend on the sea surface temperature increases imposed, but the geographical distribution of other changes, for example in the hydrological cycle, are qualitatively similar whether a uniform or a latitudinally varying change in ocean temperature is applied. This relative insensitivity of certain aspects of simulated climate to the details of the changes in ocean temperature is explained in terms of the physical processes involved. In contrast, when the first experiment is repeated with a second atmospheric model, although there are broad similarities, many aspects of the detailed regional response of the two models are found to be quite different. These regional differences can be attributed to differences in the unperturbed climates simulated by the two models.

Some of the problems of comparing simulated and observed data are illustrated using data from both sources over eastern England. The simulated climate over western Europe is assessed, and the changes in the more realistic integration with latitudinally varying changes in ocean temperature are presented. Finally, some of the outstanding problems in modelling the effects of CO_2 on climate are outlined.

1. Introduction

In recent years there has been a growing interest in the possibility that climate may be changed substantially due to increased concentrations of atmospheric carbon dioxide (CO_2) released by burning fossil fuels. Many of these conjectures are based on results from numerical models of climate. In this paper we consider various aspects of such results using examples from work carried out in the Meteorological Office supported by E.E.C. Contract CL1-030-81-UK(H).

In the first part we assess the response of an atmospheric model to increased CO_2 with prescribed increases in sea surface temperatures. The increases in sea surface temperatures were those expected to accompany the given increase in CO_2; in the first approximation a uniform increase was imposed, and in the second, the temperature increments varied with latitude. We then consider the response of a second model to increased CO_2 and a uniform rise in sea surface temperature. These two studies indicate the dependence of the simulated changes on the assumptions made in the experiment and the particular model used. The response of the hydrological cycle in summer is treated in detail as an example.

In the second part, methods of comparing model and observational data are described, and are used to evaluate the simulated climate over western Europe. Some of the changes in climate over Europe found in the experiment with a latitudinal increase in sea surface temperature are analysed. Finally areas for future research are identified.

2. Numerical simulation to determine the effect of CO_2 on climate

2.1 Choice of sea surface temperature changes

In assessing the effect of perturbations on climate, one must take into account all the elements of climate which contribute on the relevant time scale. As CO_2 is expected to increase over the next few decades, it is necessary to simulate the response of the ocean, but the major ice sheets may be regarded as 'fixed'. Although coupled dynamical models of the ocean and atmosphere have been developed, they are expensive in terms of computing resources. If the horizontal resolution of the model is degraded in the interests of economy, it is found that the simulation, particularly of the ocean, is degraded. Many recent studies (1,2,3) have used an atmospheric model coupled to a static well mixed ocean 50 to 70 metres deep. Many important processes including advection of heat by the oceans are neglected, with subsequent degradation of the model climate, though one study has attempted to prescribe the horizontal heat convergence in the ocean from climatological data (2).

Here an alternative approach is pursued. The change in radiative heating due to increasing CO_2 is small (a warming of order 5 Wm^{-2} of the troposphere and surface due to doubling CO_2 compared to an ambient tropospheric cooling of 100 Wm^{-2}), suggesting that the response of climate to increased CO_2 may be regarded as a perturbation. In the control integration, sea surface temperatures (and sea ice extents) are prescribed from climatology. In the anomaly integrations, the sea surface temperatures are derived from a series of perturbation experiments in which the change in zonally averaged net surface heating accompanying the increased CO_2 is progressively reduced towards zero (4,5). Since the annual average net surface heating at each latitude represents an implied divergence of heat in the ocean, no change in net surface heating implies that the zonally averaged meridional advection of heat is unaltered.

2.2 The model

Except where stated, all the results in this paper are from integrations made with the Meteorological Office 5-layer model (5LM)(4). It is a primitive equation model, using a quasi uniform 330 km horizontal grid. The radiative fluxes are dependent on clouds, temperature, water vapour, carbon dioxide and ozone; infra-red radiation is treated using the emissivity approximation. Seasonally varying cloud amounts, sea surface temperatures and sea ice extents are prescribed from climatology. Over land, snow is accumulated and surface albedo is a function of snow depth, where appropriate, and a soil moisture variable is used in the derivation of evaporation and runoff.

The model simulates all the main features of the global circulation, the main shortcomings being excessive surface pressure in polar regions, under and over estimation of the depth of mid-latitude depressions in southern and northern winter mid-latitudes respectively, and heavier than observed precipitation over the continents (see for example, Figure 1). Further details of the model and its climatology are given in reference (4).

2.3 Sensitivity of the simulated response to imposed changes in sea surface temperatures

In the initial experiment, CO_2 concentrations were doubled and sea surface temperatures were enhanced everywhere by 2K, as a first approximation to the oceanic response. Land surface temperatures increased by 3K, and precipitation increased by 5% (Table I).

There was a marked increase in westerly flow in mid-latitudes in winter. Large increases in precipitation occurred in existing regions of low level convergence, notably the eastern coasts of continents in summer, with decreases in some regions of the sub-tropics (for example Figure 2a). There was a general decrease in soil moisture, although some regions became moister, including part of the tropics.

Evidence from this experiment and from studies carried out elsewhere indicate that the rise in sea surface temperature accompanying doubled CO_2 should be larger in high latitudes and smaller in the tropics (1,4). Hence an additional experiment in which the sea surface temperature change increased with latitude was carried out (5) (the sea temperature changes were chosen to reduce the zonally averaged surface heating towards zero, as explained in Section 2.1). CO_2 amounts were quadrupled, and the sea surface temperature increments, ranging from 2K in the tropics to over 5K in high latitudes, were chosen accordingly. In addition, the sea ice margins were moved 6° of latitude poleward.

The land surface temperature increased by 4K, and precipitation increased by 3.5% (Table 1). Not surprisingly, in the second experiment, the changes in land surface temperature in high latitudes were considerably enhanced relative to the first experiment (assuming a quadrupling of CO_2 amounts produces twice the temperature change expected from a doubling). On the other hand, the changes in zonally averaged westerly wind and precipitation were qualitatively very similar. For example, during June to August (Figure 1b) there were increases in precipitation over the southern and eastern coasts of North America and Asia, over the tropical and southern circumpolar oceans and poleward of 55°N. There was reduced precipitation in northern mid-latitudes and in parts of the subtropics. There were some areas where discrepancies occur, including the Sahara and the Middle East where the reductions in rainfall found in the first experiment (Figure 2a) are less extensive in the later integration (Figure 2b). However throughout the year the response in hydrological cycle was in general very similar.

The reason for this similarity is that in each study the atmosphere becomes warmer and moister (Table 1). In the absence of marked changes in circulation, this enhances the convergence and divergence of moisture in the control integration, so that regardless of the details of the warming, the patterns of change are similar. There is also a reduction in the transient eddy kinetic energy in mid-latitudes, implying weaker and/or less frequent disturbances in both studies which may contribute to the reduction in precipitation over the northern continents in summer. A more detailed discussion of these changes is given elsewhere (4,7).

In both experiments, much of the northern mid-latitude continents became drier in summer (7). The changes were more pronounced in the second experiment though this may be because the response to the larger perturbation shows more clearly above the year to year variations inherent in the model. Other studies made with atmospheric models coupled to a simple representation of the ocean produced a drying in mid-latitudes in summer (6). Reduced precipitation, increased radiative heating of the surface, and earlier snow melt in the warmer climate leading to a longer summer drying season all contribute to this phenomenon. Again, the responses are alike because the same physical processes operate, even though the changes in sea surface temperature or the models used are different.

2.4 Sensitivity of different models to the same perturbation

The experiment in which CO_2 was doubled and sea surface temperatures were increased by 2K was repeated using the Meteorological Office 11-layer model (11 LM, see Slingo and Wilson, 1984[1]). The main differences in formulation are listed in Table II. Note that the 11LM, by virtue of its regular latitude/longitude grid, has much finer resolution in high latitudes, and uses different boundary layer and convection schemes.

In the 11LM the southern circumpolar depression belt is deeper, and the westerly flow in northern middle to high latitudes is stronger. Furthermore the 11LM tends to produce its most intense precipitation over the tropical oceans, whereas the 5LM gives excessive precipitation over land (Figures 1, 3a). A comparison of the simulations of the 5LM and an older version of the 11LM on a 200 km quasi uniform grid is given in reference (8).

The increases in land surface temperature and precipitation were similar to those in the original experiment (Table I). Again there was an increase in westerly flow in middle latitudes in winter. However the increase is shifted poleward relative to the 5-layer model experiment, consistent with the maximum in westerly flow in the control integrations being further poleward in the 11-layer model than in the 5-layer model. The zonally averaged changes in precipitation were similar in both models, with increases in high latitudes and the tropics throughout the year and in middle latitudes in winter, with little change or slight decreases in the subtropics. There was less rainfall over the northern mid-latitude continents in the summer. However, there were considerable discrepancies in the detailed regional changes which again reflect the differences in the models' climatologies. Thus, for example, from June to August, increases in precipitation along the southern and eastern coasts of North America and Asia were predominantly over the ocean in the 11-layer model (Figure 3b) but over land in the 5-layer model (Figure 2a). It should be noted that this discrepancy is consistent from year to year, but some of the small scale changes in both Figures 2a and 3b arise from year to year variations which occur by chance. As in the 5-layer model experiments, the continental surface in northern mid latitudes in summer tends to dry out more in the anomaly integration.

In section 2.3 it was demonstrated that a climate model may respond in a similar manner to different perturbations as the same physical mechanisms may be involved. In this section we have seen that different models can produce a divergent response, particularly on smaller scales, if the unperturbed circulations are not the same. This is consistent with the argument advanced earlier that the projected increases in CO_2 may be regarded as a perturbation, so that the simulated response is strongly dependent on the unperturbed climate.

3. Interpretation of model data and simulations of climate over western Europe

3.1 Comparison of simulated and observed data

In the previous sections we have considered the large scale response of a particular model to increases in CO_2, and some of the accompanying uncertainties. Even if these uncertainties can be resolved, there remains

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1 To appear with this paper in the proceedings of the European Climatology Symposium, Sophia Antipolis, 2-5th October, 1984.

the problem of comparing model gridpoint data, which can be regarded as a mean value over an area several hundred kilometres square, often averaged through the lowest 100 to 1000 metres of the atmosphere, with observational data at a given location, usually taken at a specific time a few metres above the ground. For climate impact studies, not only mean data are required, but also the frequency of extreme events and so on. We consider as an example the simulated time series of temperature and precipitation at a grid box over eastern England (9).

The annual mean simulated surface temperature, 3.8°C, is 5.6°C colder than the annual mean Central England Temperatures (averaged from 1959 to 1973, (10)). The Central England Temperature series is a mean of maximum and minimum temperatures, whereas the model temperatures are sampled at midnight. Observations of midnight temperature at Hemsby and Crawley indicate that 8°C is a more reasonable estimate of the annual mean midnight temperature for eastern England. The model temperature is for the surface, and more akin to a ground (grass) temperature rather than a screen temperature taken at a height of 1.5 metres, as in the Central England Temperature time series. A comparison of grass and screen temperatures at stations in eastern England indicate that the grass temperatures are typically 2°C lower than the corresponding midnight screen temperatures; hence we conclude that the model surface temperatures are about 2°C too cold. A similar comparison of temperatures in the bottom layer (at about 900 mbs) suggests that the model is only about 0.5°C too cold at that level. The frequency distribution of the simulated and observed daily temperatures (with the mean and annual and semi-annual cycles removed) are remarkably similar, except for the large number of very cold events in the modelled distribution (Figure 4). This 'cold tail' is a manifestation of the greater than observed frequency of easterly flow during late winter and spring, which leads to unrealistically low temperatures over much of western Europe.

It was noted earlier that the simulated precipitation is higher than observed over the continents, and this is true over western Europe, except for gridpoints bordering the Mediterranean. The seasonal variation is qualitatively realistic, except for a few isolated gridpoints in Central France and Germany where the observed summer maximum is not reproduced. As precipitation is poorly correlated in space, the model data for eastern England have been verified against daily precipitation averaged over 144 stations in England and Wales during 1971 to 1973. The model substantially overestimates the frequency of days with about 5 mm of precipitation (Figure 5). Note also that the heaviest precipitation produced in the model is considerably less than in the England and Wales rainfall. Although there are difficulties in measuring daily precipitation of less than a few tenths of a millimetre, it is clear that the model grossly underestimates the number of dry days (see also Table IV).

3.2 Simulated climate over western Europe and the response to increased CO_2

Having outlined some of the methods of comparing model and real data, we now consider some of the detailed changes in climate over western Europe found in the 4 x CO_2 integration described in section 2.3. It is evident from the paper so far that there is much to be done before predictions of regional climate from climate models can be used with any confidence. However, it is important that methods of translating changes in model gridpoint data to parameters from which the economic impacts can be assessed should be developed and tested so that they are available when more reliable forecasts can be made. Here, two examples are considered, namely changes in precipitation and in the frequency of occurrence of low temperatures. A more detailed account of changes over western Europe is given in reference (11). The stations used for comparison are Raunds (eastern England), Muenchen (West Germany) and Capo Palinuro (southern Italy).

Enhancing CO_2 concentrations and ocean temperatures produces a surface warming which throughout northern Europe is greatest in winter and spring, but around the Mediterranean is a maximum in summer or autumn. The overall rise in temperature leads to a decrease in frequency of low temperatures (Table III). However, this decrease is enhanced by stronger westerly flow in winter, which is associated with a reduction in frequency of cold easterly outbreaks. If, for example, the annual mean increase in surface temperature over eastern England were applied to the time series of temperatures from the control integration, the frequency of midnight temperatures below zero would fall from 76 to 10 per year. In the 4 x CO_2 integration, on average only 2 occurrences per year were found.

Although the frequency of days with measurable precipitation is grossly overestimated (Table IV), the model results can be used to indicate the sense of the changes in precipitation in the warmer climate. In general, northern and western Europe are wetter throughout the year except in summer, whereas southern and especially south eastern Europe receive less rainfall throughout the year. Eastern England and Central Germany have more precipitation in winter, although the frequency of daily precipitation changes little (Table IV). In contrast, rainfall at the gridpoint in southern Italy is reduced in the mean and occurs less frequently throughout the year. By applying a simple statistical model (12), one can estimate the statistical significance of the changes in both mean precipitation and the frequency of precipitation (Table IV). Thus for example, the changes in precipitation over southern Italy are significant at the 95 per cent level of confidence in both winter and summer, but only the change in mean summer precipitation is significant at the gridpoint in Central Germany.

4. Concluding Remarks

We have examined some of the potential and shortcomings in the use of numerical models for the prediction of climate change. Recent experiments using climate models with a simple representation of the ocean have indicated an equilibrium global mean surface warming of about 4°C on doubling CO_2. These studies attribute a substantial fraction of the warming to either changes in cloud cover (2) or sea ice (3). Further research is needed to clarify the role of cloud cover and sea ice in climate change, and to use models which include full representation of the oceans.

Both studies to date have considered the equilibrium response to increased CO_2 concentrations and should not be regarded as predictions. The response of climate to the observed gradual increase in CO_2 amounts is expected to be slowed by the large thermal inertia of the oceans. This retardation depends critically on the rate at which heat is mixed down into the deep ocean, and many of the processes involved are poorly understood.

Undertaking research on climate and climate change is a long term commitment, and progress on a year-to-year basis may appear slow. It will be some years before we can predict regional changes in climate with any confidence. However, our understanding of the physical basis of climate has improved considerably over the last decade, and we can expect significant progress in the decade to come.

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Figure Captions

1. Total precipitation simulated by 5LM during June, July and August (3 year mean). Contours at 0.5, 1, 2, 5 and 10 mm/day. Light stippling where less than 1 mm/day, heavy stippling where greater than 5 mm/day, solid shading where greater than 10 mm/day.

2. Changes in precipitation simulated by the 5LM during June, July and August (3 year mean). Contours at -2, -1, 0, 1 and 2 mm/day. Areas of decrease are stippled.

(a) due to doubling atmospheric CO_2 and a uniform 2K increase in sea temperatures.

(b) due to quadrupling atmospheric CO_2 and rises in sea temperatures which increase with latitude.

3. (a) Total precipitation simulated by 11LM during June, July and August (8 year mean). Contours at 1, 2, 5, 10 and 20 mm/day, hatched where greater than 5 mm/day.

(b) Changes in precipitation in the 11LM during June, July and August due to doubling CO_2 and a uniform 2K increase in sea temperatures (3 year mean). Contours at -2, -1, 0, 1 and 2 mm/day, areas of decrease are hatched.

4. Frequency distribution of surface temperature (annual mean and annual and semi annual cycles removed). Solid line, daily Central England temperature series (1100 days of daily data commencing January 1st 1971). Dashed line, 1100 days of data simulated at a grid box in eastern England by the 5LM.

5. Frequency distribution of logarithm of daily precipitation. Solid line, 1100 days of daily data commencing January 1st 1971, averaged over 144 stations in England and Wales. Dashed line, 1100 days of data simulated at a grid box in eastern England by the 5LM.

Table I Changes due to increasing CO_2 and enhancing sea surface temperatures

Experiment	Tropospheric Temperature (°C)	Atmospheric Humidity (%)	Land Surface Temperature (°C)	Precipitation (%)
2 x CO_2 (5LM)	3.02	18	2.86	5.0
*4 x CO_2 (5LM)	2.44	15	4.00	3.7
2 x CO_2 (11LM)	3.08	20	3.05	5.6

* Differences halved to allow comparison.

Table II Main differences in model formulations

5 LAYER MODEL	11 LAYER MODEL
GRID 5 layers, equally spaced	11 layers, concentrated near surface and tropopause
300 km in horizontal	2.5° x 3.75°
BOUNDARY LAYER	
1 layer (up to σ = 0.8)	3 layers (up to σ = .79)
Explicit boundary layer height	Vertical diffusion, "Clarke" scheme
Bulk aerodynamic formula	Drag coefficient continuous
Stable/Unstable, land/sea drag coefficient	function of stability and roughness length
Full evap. when soil moisture = 10 cm	Full Evaporation - 5 cm
Run off when soil moisture = 20 cm	Run off - 15 cm
RADIATION	
Temperature and humidity interpolated to 10 equally spaced layers for radiation.	Fluxes calculated on model layer boundaries
No absorption of reflected solar beam.	Reflected solar beam absorbed
Snowfree albedo a function of latitude	Constant (= .2)
Albedo over snow a function of snow depth	Constant (= .5)
Cloud amounts, albedos similar	
PENETRATIVE CONVECTION	
Detrains only at upper levels	May entrain and detrain at any level.
May affect a given layer more than once/timestep.	Only affects a given layer once/timestep.
DIFFUSION	
Diffusion of potential temperature θ	Diffusion of aT + bθ
Non linear diffusion of humidity	Linear diffusion of humidity.

Table III Number of days/year with 00 GMT temperatures below 0°C

GRID POINT	CONTROL	4 x CO_2
Eastern England	76	2
Central Germany	187	49
Southern Italy	55	6

Table IV Average number of days per season on which precipitation exceeded a given threshold

GRID BOX	THRESHOLD (mm)	WINTER O	WINTER C	WINTER A		SUMMER O	SUMMER C	SUMMER A	
England	0.25	45	71	71	+	37	86	77	– *
Germany	0.1	47	86	88	*	49	89	88	–
Italy	1.0	34	52	35	– *	9	10	4	– *

O = Observations (see text), C = Control, A = 4 x CO_2

+/- increase/decrease in mean precipitation significant at 95% level of confidence

* change in frequency of precipitation significant at the 95% level of confidence.

TOTAL PRECIPITATION (MM/DAY) JUNE, JULY, AUGUST

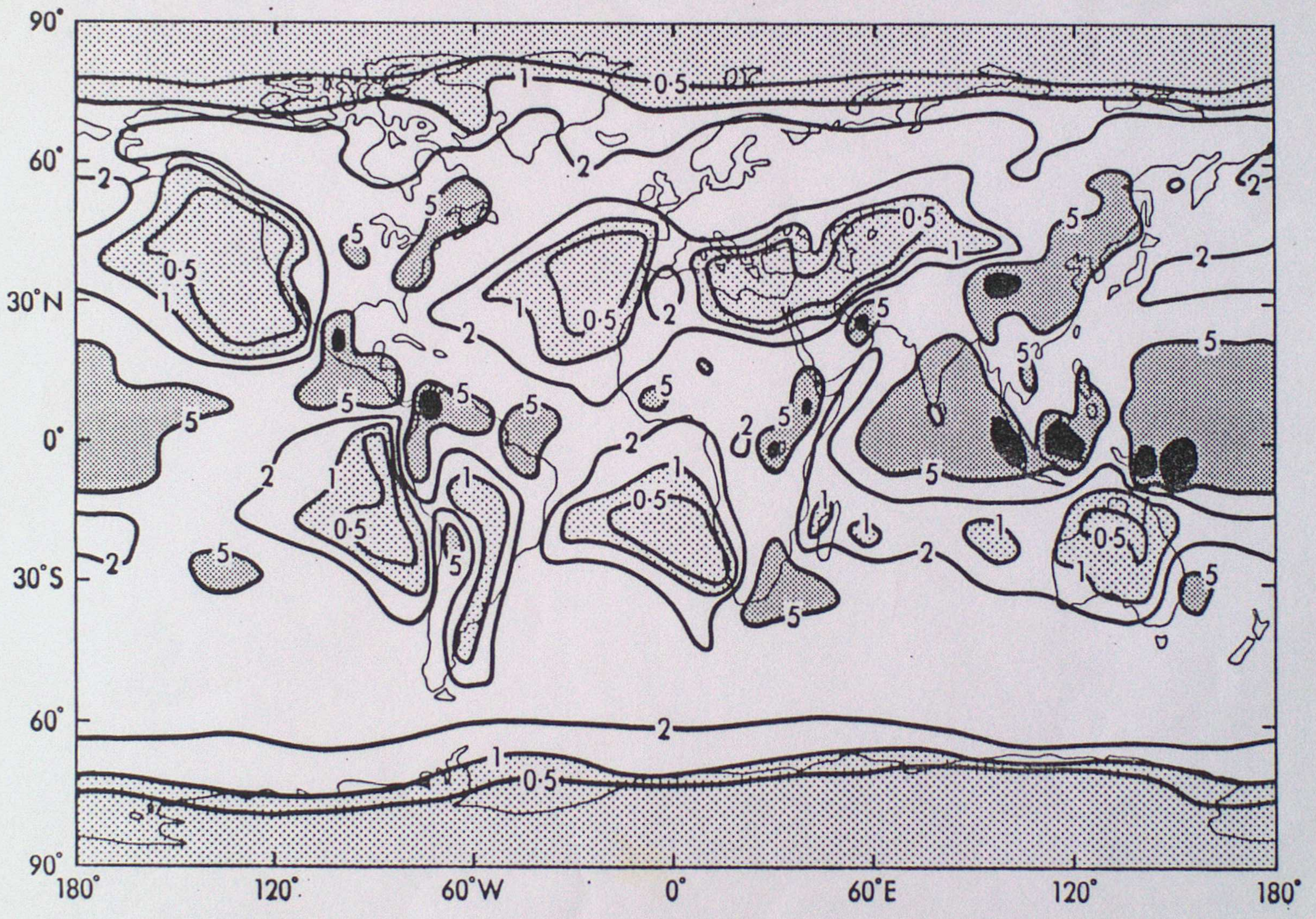

Figure 1

CHANGES IN PRECIPITATION DUE TO ENHANCING SSTs AND DOUBLING CO_2 (MM/DAY)
JUNE, JULY, AUGUST

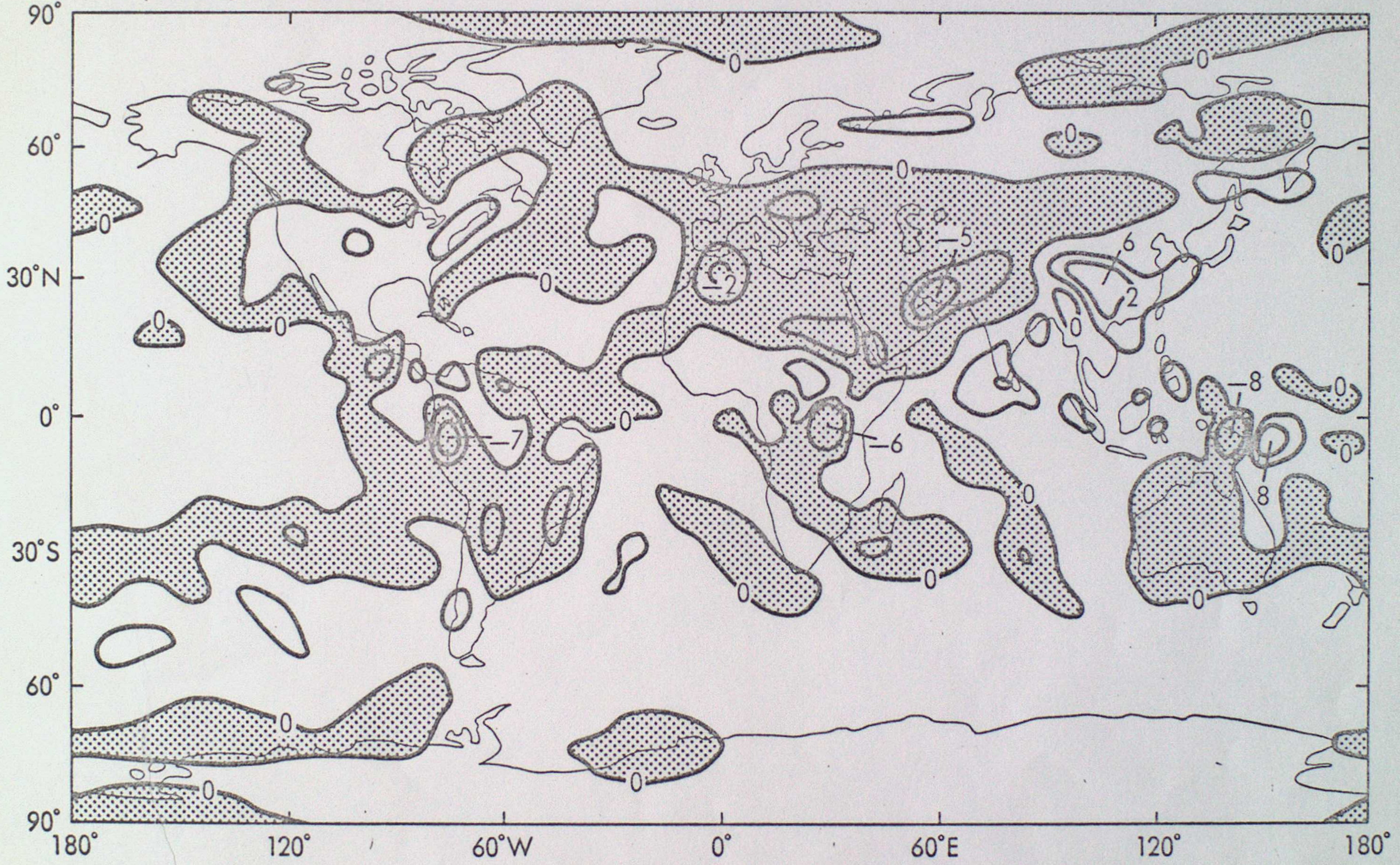

Figure 2 (a)

CHANGES IN PRECIPITATION DUE TO QUADRUPLING CO_2
AND ENHANCING SSTs (mm/day)
JUNE JULY AUGUST

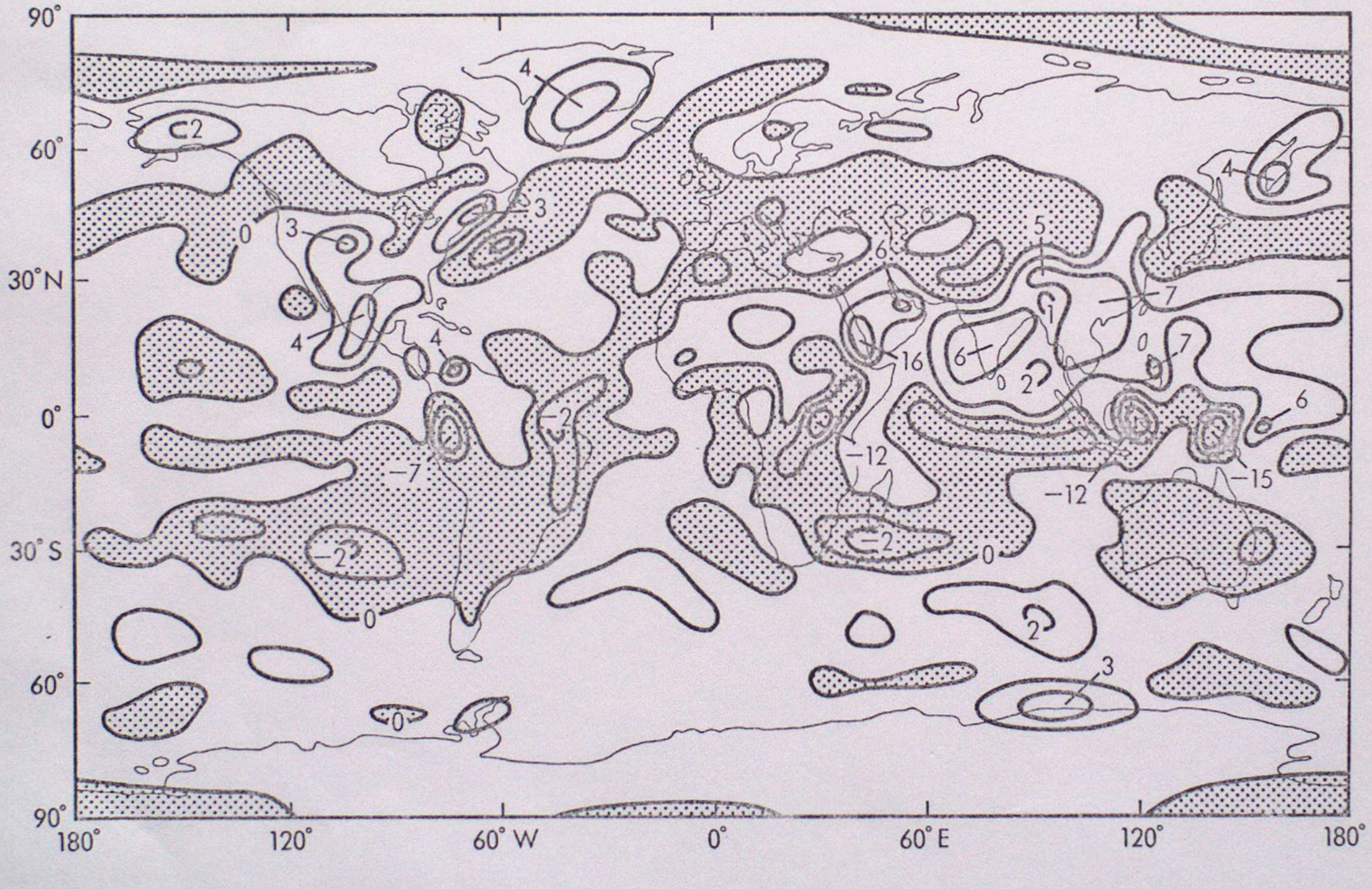

Figure 2 (b)

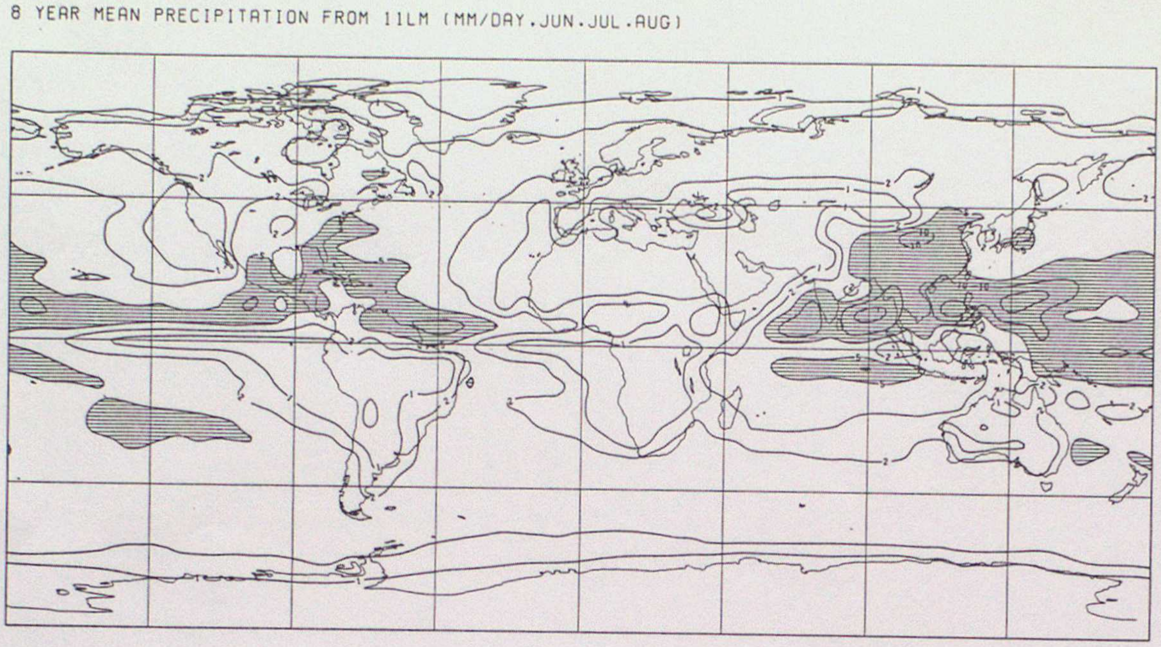

Figure 3 (a)

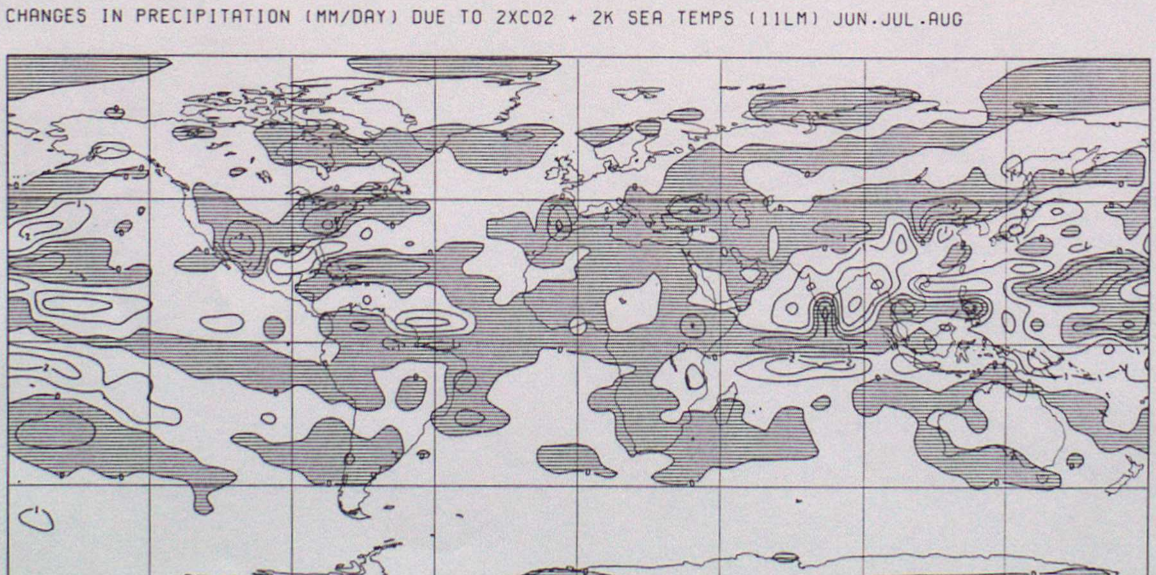

Figure 3 (b)

FREQUENCY DISTRIBUTION OF SURFACE TEMPERATURE

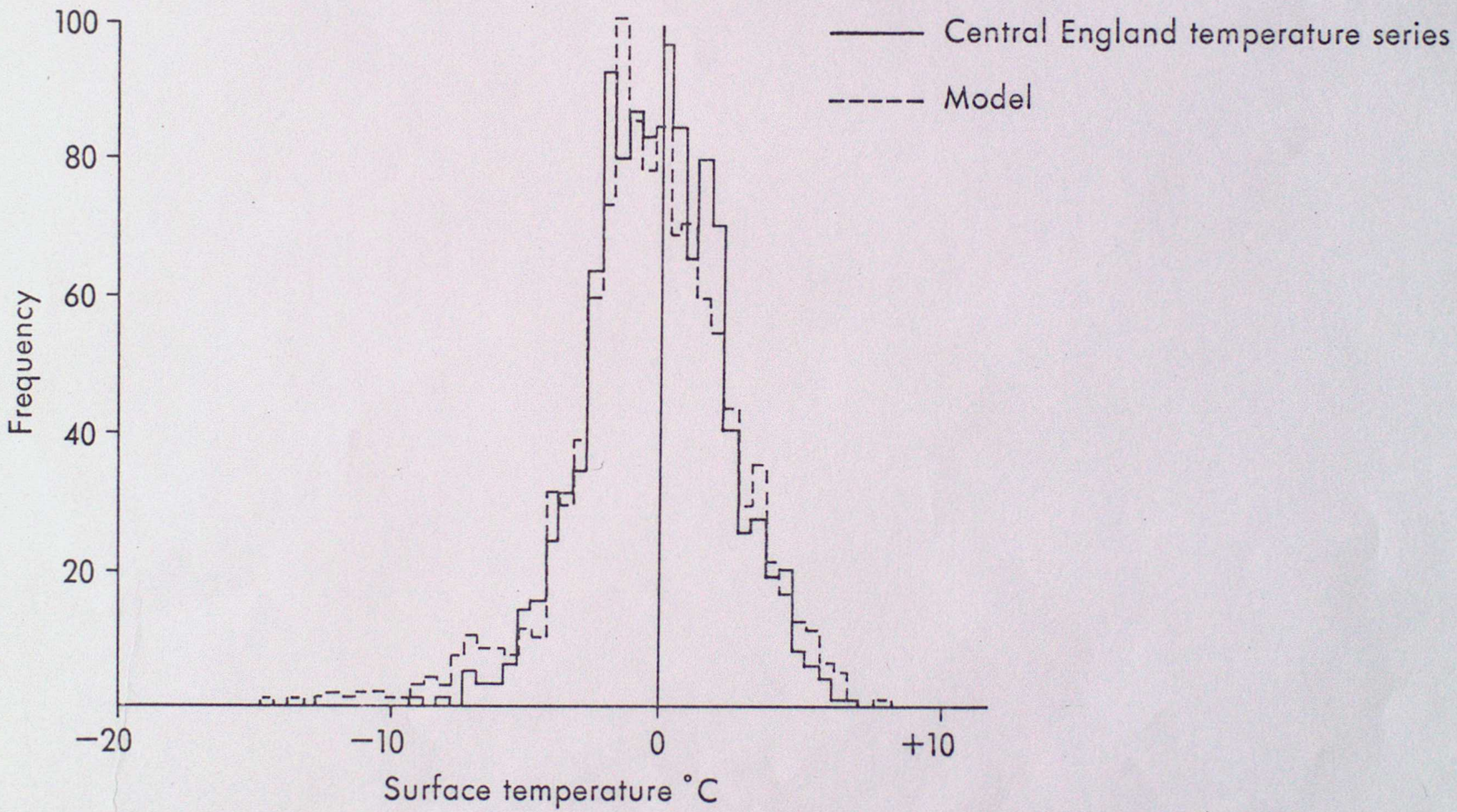

Figure 4

FREQUENCY DISTRIBUTION OF LOGARITHM OF DAILY PRECIPITATION

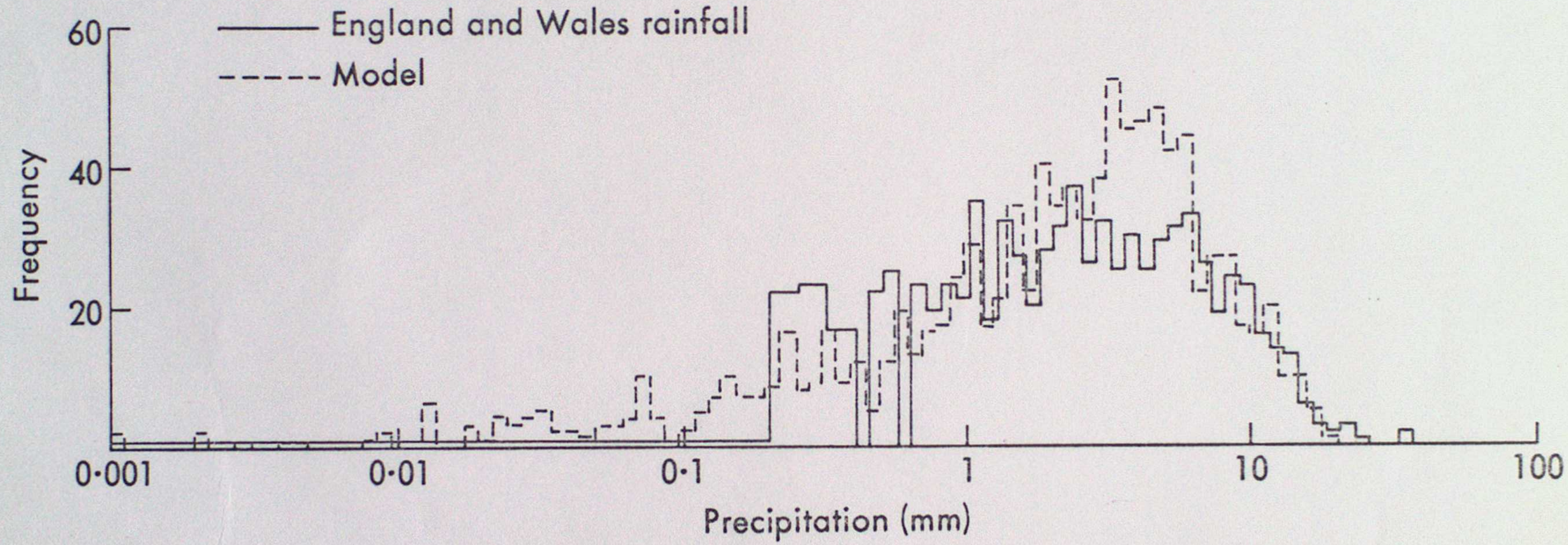

Figure 5