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On the sensitivity of a general circulation model climatology to changes in cloud structure and radiative properties

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ABSTRACT

A numerical study, using a general circulation model of the atmosphere, has been carried out to investigate the sensitivity of the model-generated climatologies to changes in the cloud characteristics. In particular, we have investigated the effects of lowering the cloud base by 200 mb and, in a separate experiment, the effects of changing the solar radiative properties of the clouds.

The results of this study indicate that the model-generated climatology is more sensitive to changing the radiative properties than to altering the cloud base position. Large-scale changes occur in the surface heat budget and hydrological cycle. These conclusions indicate the need for more accurate studies of cloud systems and their parameterization in numerical models.

1. Introduction

The importance of understanding the manner in which a change in the cloud amount and distribution of cloudiness may act as a climatic component has been accentuated by concern over the possibility of inadvertent modification to the global climate by Man's activities (SMIC Report, 1971). For example, a 2 K increase in global surface temperature has been predicted by the radiative convective model of Manabe and Wetherald (1967) for a doubling of the concentration of CO_2. Also, a 3.5 K decrease in global surface temperature has been suggested by the calculations of Rasool and Schneider (1971) for a factor of 4 increase in atmospheric aerosols. Neither of these studies, nor those of Manabe and Wetherald (1975), using a general circulation model, have incorporated the possible effects from simultaneous variations in cloudiness. As Schneider (1972) indicated, the neglect of these interactions is a weakness of these earlier studies since the precise manner in which the cloud effect can modify the meteorology will depend critically on the local characteristics, especially the surface albedo. General circulation studies which incorporate a zonally symmetric distribution of clouds, or a fixed climatological distribution have at most a very limited value in our attempt to understand the interaction between clouds, atmospheric motions and climate. Herman et al. (1980) have shown that the failure to introduce interactive cloud and radiation schemes will greatly affect the radiative forcing in the model.

The central problem is that we currently know very little about clouds, the temporal and spatial distributions that would specify a climatology and, at the same time, provide data for inclusion in general circulation and climate studies. In principle, satellite observations should provide the required measurements since the current systems of polar orbiting and geostationary systems provide surveil-

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lance of the temporal and spatial changes (see, for example, Vonder Haar and Suomi (1971), Winston (1971), McCleese and Wilson (1976), Menzel et al. (1980), Schenk et al. (1975), Smith et al. (1973), Saunders and Hunt (1980) and Minnis and Harrison (1980)). While these methods do provide some estimate of the cloud properties, they do not provide any information on the vertical structure of the clouds and the varying amounts that may be found at different levels in the atmosphere. Furthermore, the precise accuracy in determining the cloud top parameters is unknown. But both Schneider (1972) and Ohring and Adler (1978) have shown that a decrease of only 1 km in cloud top and cloud base produce a 0.6 K increase in surface temperature. That is, the greenhouse effect is reduced as the altitude of the cloud base increases.

While these studies of the sensitivity of the global heat balance to cloud changes are important, they do not give any indication of the likely feedback of these effects upon the general circulation, or meteorological variables such as rainfall and evaporation. Schneider et al. (1978) carried out a sensitivity study of the effects of cloud on the surface heat budget through prescribing changes in the ocean temperature in specified regions. This study serves to illustrate some possible relationship between sea surface temperature effects and cloud changes.

In this paper, we have investigated the fundamental problem of the potential usefulness of the presently available cloud information for studying the relationship of changes in cloudiness and climatic change by investigating the sensitivity of a general circulation model climatology to changes in the cloud structure. We assume that the initial cloud distribution and radiative properties are parameters that can be provided directly from the satellite measurements. Then other GCM experiments are set up firstly with changes to the cloud base and then to the radiative properties, in order to assess the sensitivity of these model-generated climatologies to these particular changes. The variations in cloud base position are particularly important since this essential cloud parameter cannot yet be determined from satellite studies.

These cloud experiments, described in detail in Section 2, provide some insight into the cloud/dynamics interaction which remains one of the basic problems of investigation in atmospheric physics.

2. Cloud experiments and analysis methods

The five-level GCM of Corby et al. (1972), modified by Hunt (1975) to incorporate interactive clouds and radiation, is used as a basis for this particular study. The radiative transfer characteristics of the model are calculated by parameterizations of the short-wave and long-wave processes. The radiative effects due to water vapour are controlled by the model's relative humidity which is also used to predict the amount of cloud that occurs at different levels. The model has three layers of cloud whose positions are specified in terms of the sigma coordinate ($\sigma = p/p_*$, where p_* = surface pressure). High clouds are specified in the region $\sigma = 0.2$–0.3, middle cloud $\sigma = 0.4$–0.6, and low cloud $\sigma = 0.6$–0.8. The amount of cloud is predicted through a linear relationship with the relative humidity (Hunt, 1975). A detailed description of the model and the climatology predicted for January conditions is given in Hunt (1975).

In this paper, we have assumed that the satellite studies would provide only the cloud amount (C), cloud top position and reflectivity (R) at any location on the globe. As a consequence, these values would therefore be vertically averaged and would not provide any indication of the actual thickness of the observed cloud. In Table 1, we have set out the characteristics of the individual experiments.

Table 1. *Characteristics of the cloud experiments*

Experiment	Cloud position (mb)	Radiative properties
*RAT*1	400–600	$R = 0.5; A = 0.15; T = 0.35$
*RAT*2	400–800	$R = 0.5; A = 0.15; T = 0.35$
*RAT*3	400–800	$R = 0.5; A = 0.35; T = 0.15$

We assume for convenience that the cloud top has been estimated to be at the 400 mb level and the cloud is 200 mb thick. In the GCM, the cloud will then occupy a complete layer. The visible reflectivity of the cloud is assumed to be estimated to be $R = 0.5$. Since the cloud transmissivity (T) and absorptivity (A) will not be determined directly from satellite measurements, their individual values have been estimated as $T = 0.35$ and $A = 0.15$

respectively. The experiment *RAT*1 represents the control experiment for the satellite data. In order to assess the effect of changing the cloud base, the experiment *RAT*2 has been carried out in which the cloud thickness has been increased to 400 mb, with the base now positioned at the 800 mb level. But, the cloud radiative properties are poorly known. While we have initially assumed that the reflectivity of the cloud system is known, this still leaves the two remaining radiative parameters undetermined. As a result, the values of T and A have been changed in *RAT*3 in order to assess the sensitivity of the model generated climatology to these changes.

The changes in these cloud experiment climatologies are assessed through a comparison with the January simulation produced by Hunt (1975). In the usual way, the time integration of the GCM is carried out for a period of about 80 days with the resulting meteorological parameters analysed over the final 30-day period. In all the experiments, the cloud and radiative properties are interactive and generated from the model parameters as set out in Hunt (1975). In each grid square, a partial cloudiness (C) is determined by the procedures described previously in Hunt (1975). These cloud models are summarized schematically in Fig. 1. The analysis of sensitivity studies using GCM's must be carefully assessed due to the model's own variability resulting from the build up of computational errors (see, for example, Chervin and Schneider (1976a, b)). In order to be confident in the results we present in Section 3 of this paper, we have analysed the perturbation experiments by two procedures. Firstly, we have applied the student t-test method. We than consider a change in a physical parameter to be statistically significant at the 2.5% level when $t \geqslant 2.5$. Secondly, we have carried out a further integration in which the initial temperature field has been randomly perturbed by up to ± 2.5 K (r.m.s. $\pm$ 1.15 K). The differences between the resulting climatologies and those obtained by the standard integration (Hunt, 1975) are a measure of the natural variability of the model-generated fields.

Using these procedures, we consider the changes in the model climatologies to be real if they exceed *both* the natural variability *and* satisfy the statistical analyses as shown in the following section. The requirement that both these conditions

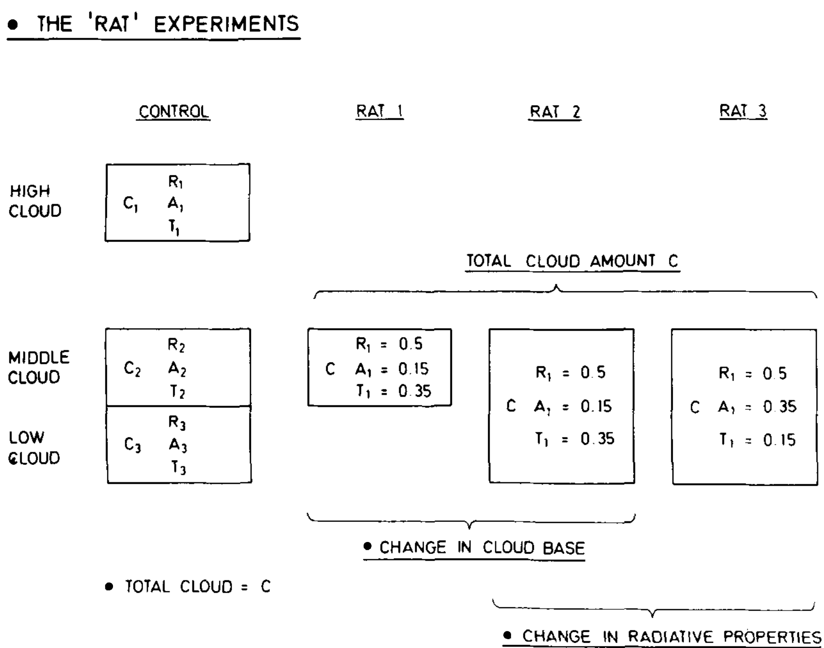

Fig. 1. A summary of the *RAT* experiments investigated in this paper.

should be satisfied is a stringent test. Therefore, this is a stronger requirement than relying on the statistical tests alone, which assume uncorrelated and normally distributed data.

3. Results

In assessing the effects of the changes in the model calculations, we have considered the magnitudes of the differences in the various model-generated climatological states. Since we are interested in the surface parameters, which are controlled by the model itself, the analysis has been applied only to those grid points concerned with land and ice. In these integrations, the sea surface temperature remains constant. Consequently, to include all the surface grid points in the analysis would then not provide a true indication of the effect of changes in the cloud structure and radiative properties.

3.1. *Surface temperature*

The natural variability in the surface temperature is shown in Fig. 2a through the difference $T_{STAN} - T_{RAN.PERB}$. These results show the strong latitudinal variations that occur particularly in the baroclinic zone at 60° N. At this latitude, the "noise" in the GCM is equivalent to a surface temperature change of more than 6 K which will result from the effects of small changes in the fronts that are located in this region. In the equatorial region, however, the changes are considerably smaller, and the noise is equivalent to changes of less than 1 K in the region ±10°.

Fig. 2b shows the corresponding changes in the cloud experiments. It is apparent that the surface temperature changes in the northern hemisphere are not significant for either set of experiments. However, the largest changes occur in the southern hemisphere, which is more understandable since this portion of the globe will then be experiencing summer conditions. The largest changes appear to occur when the radiative properties of the clouds are changed (Fig. 3). The global temperature in this case is −1.14 K. Although the t value is 2.58, this temperature change is less than the natural variability of the model (Table 2) and cannot be considered to be significant.

Lowering the cloud base produces a smaller global temperature change of −0.4 K, which again is not significant. Even on a zonal scale, there are no major changes that are statistically significant (Fig. 2b).

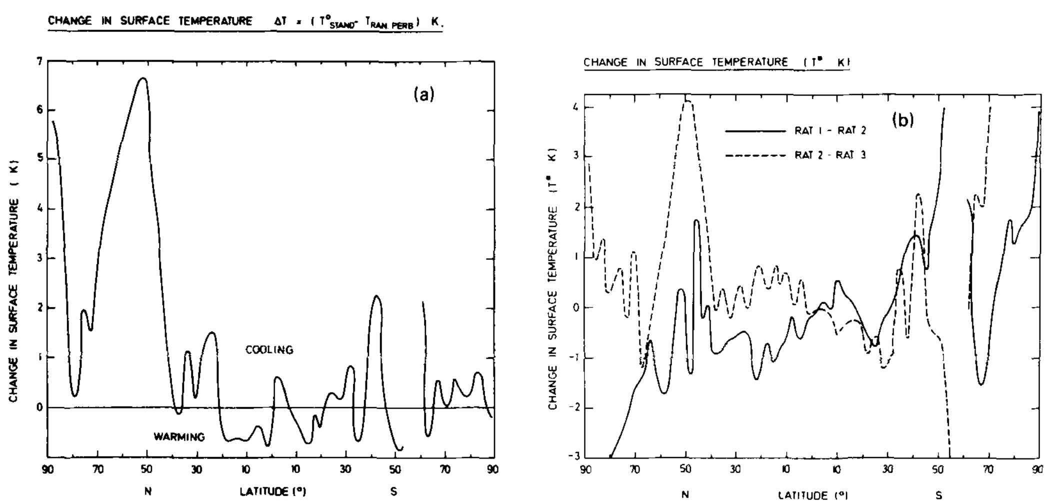

Fig. 2. (a) The change in the zonally averaged surface temperature between the standard model and the random perturbation experiment as a function of latitude. (b) The same as for (a) for *RAT1–RAT2* (——) and *RAT2–RAT3* ----. Note that the isoline is not continuous between 55–60° S since this region is all ocean, and these temperatures are not directly altered by the model.

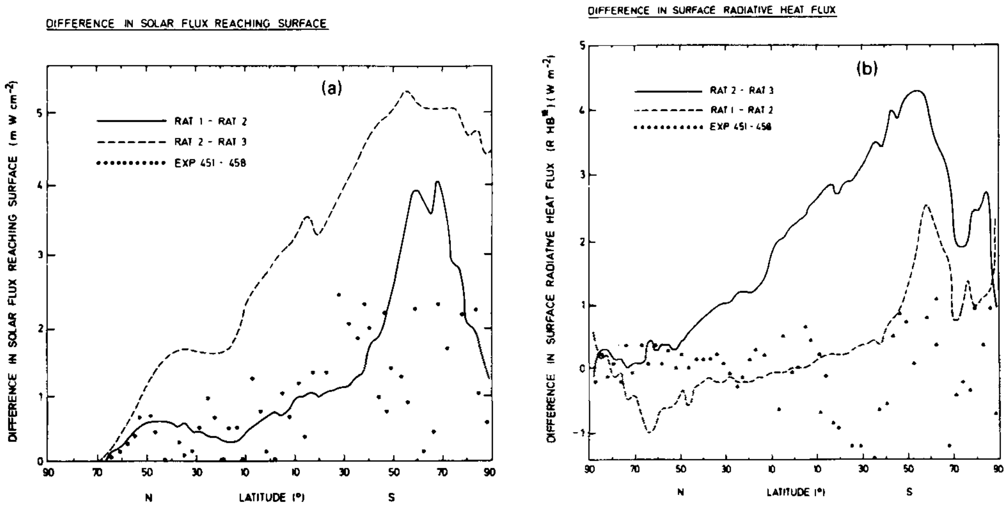

Fig. 3. (a) Difference in the zonally averaged solar flux reaching the surface as a function of latitude *RAT*1–*RAT*2 ——; *RAT*2–*RAT*3 ––––; and the random perturbation effect ····· (b) The same as (a) for the surface radiative heat flux.

Table 2. *RAT experiments—global changes*

	*RAT*1–*RAT*2 Change position of cloud base		*RAT*2–*RAT*3 Change radiative properties		
	Change	*t*	Change	*t*	Clim-random pert. Natural variation
Surface temperature (K)	−0.4°	0.15	−1.14°	2.58	1.44
Evaporation (mm d^{-1})	−0.326	4.5	0.665	8.9	0.008
Rainfall (mm d^{-1})	−0.328	6.3	0.677	10.4	0.008
Sensible heat (W cm^{-2})	351.7	2.8	773.9	4.03	−60.3
Surface radiative heat balance	0.003	7.45	0.029	110.15	−0.003

3.2. *Surface solar flux*

The behaviour of the surface temperature (T^*) will mask the individual changes that have occurred in the radiative fluxes which control the greenhouse effect. In Fig. 3a, the differences in the solar flux reaching the surface for the cloud experiments is compared with the corresponding changes due to the random variations in the model. The effect of altering the cloud radiative properties produces a change in the surface solar flux that is everywhere significant. The hemispheric and global components of these changes are given in Table 3, which emphasizes the large changes that occur on all spatial scales.

Changing the position of the cloud base also causes variations in the hemispheric surface solar fluxes that are larger than the natural variation of the model. The absorption of solar radiation within the atmospheric path will be modified now, but not as much as altering the basic absorption properties of the cloud (Fig. 3a). The largest change occurs in the neighbourhood of 50–70 °S where the change is more than twice that of the model's noise level.

3.3. *Surface radiative heat balance*

The results in Fig. 3b again show that the changes in cloud radiative properties cause signifi-

Table 3. *Sensitivity of surface radiation balance to changes in cloud structure* ($mW\ cm^{-2}$)

	Surface solar flux			Net long-wave surface flux						
	NH	SH	Global	NH	SH	Global	Surface radiative balance			
*RAT*1 / *RAT*2	0.419	1.605	0.977	0.558	0.767	0.698	−0.279	0.628	0.209	Change of cloud base
*RAT*2 / *RAT*3	1.396	4.048	2.722	0.209	0.558	0.349	0.977	3.071	2.024	Change of cloud radiative properties
Climat. random pert.	−0.139	−0.769	−0.419	−0.139	−0.139	−0.139	−0.699	−0.419	−0.209	Natural variation

cant changes at every latitude, in addition to huge hemispheric and global variations (Table 3).

Altering the position of the cloud base causes more localized effects. Naturally, the results will be influenced by the results given in Section 3.2. The strongest effect will result from the change in the downward flux from the cloud base. In the northern hemisphere, the largest changes occur between 30–70° N and in the southern hemisphere between 50–70° S. The variations in the equatorial region do not appear to be significant.

3.4. *Evaporation*

The differences in evaporation for the two sets of experiments are shown in Fig. 4a and again they are large compared with the changes which result from the random perturbation study.

When changing the cloud properties causes a change of 0.665 mm/day in the global evaporation (~16%), this compares with a change of only 0.008 mm/day in the random perturbation study. Since the t value is ~8.9, this confirms that the change in cloud radiative properties causes a significant change in the global surface evaporation. It can be seen from Fig. 4a that the largest changes occur at 30° N and between 10–50° S. Since the t statistic in these regions exceeds the criterion of 2.5 (Fig. 4b), we see that these variations are also significant. (This is in agreement with the changes in solar flux and surface radiative balance found in Sections 3.2 and 3.3.)

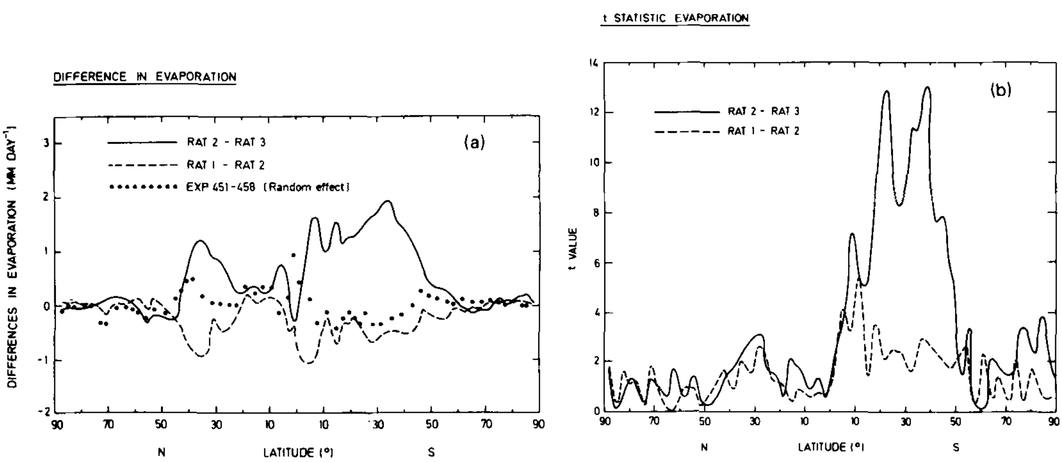

Fig. 4. (a) The changes in the zonally averaged evaporation as a function of latitude for the experiments. (b) The zonally averaged student "t"-test statistic for the differences in *RAT*1–*RAT*2 ---- and *RAT*2–*RAT*3 —— as a function of latitude.

The variation in the position of the cloud base causes smaller changes in the evaporation which do not appear to be significant apart from the region at about 30° N and the equatorial region from 0–20° S. The global change is 0.326 mm/day (~8%), which corresponds to a t value of ~4.5 which would appear to be significant.

3.5. *Sensible heat*

Although the surface sensible heat flux is extremely variable, the changes caused by these experiments would seem to be within the natural variation of the model. These changes do not appear to be significant.

3.6. *Rainfall*

The changes in the rainfall distributions are shown in Fig. 5a. Altering the cloud properties causes a global change of 0.677 mm day^{-1} (~16%) which compares with a change of 0.008 mm day^{-1} as a result of the random perturbation experiment. The t value of the former change is 10.4, which suggests that the change in the cloud radiative properties produces a significant change in global rainfall.

On a zonal scale, we see that the largest changes occur in the region 30–50° S and ~30° N. The t statistics support this claim that the changes in these regions are significant (Fig. 5b).

Changing the position of the cloud base causes a global change in rainfall of −0.328 mm day^{-1} (~8%). The zonal distribution given in Fig. 5b indicates that the changes are very close to the natural variation of the model and therefore cannot be considered to be significant.

3.7. *Changes in atmospheric temperature*

In Fig. 6a, we illustrate the changes in atmospheric temperature between the standard and random perturbation integrations. The largest changes occur in the northern latitudes between 50–70° and are primarily confined to the surface. The changes in the equatorial region are generally less than 0.5 K.

Fig. 6b shows the changes in atmospheric temperature which result for changes in the base of the cloud, and the corresponding t statistics are given in Fig. 6c. Large significant changes are indicated in both hemispheres, and are indicative of the changes in the atmospheric heating/cooling which result from representing the cloud in a small layer.

Figs. 6d and 6e show the corresponding atmospheric changes which result from changing the radiative properties of the couds. The changes in the equatorial region and the southern hemisphere are very large as one would expect, since this is the summer hemisphere where the increased solar absorption by the cloud is emphasized. Their significance is apparent both from the statistical t values and from where they are compared with the changes given in Table 4 and Figs. 6c and 6e.

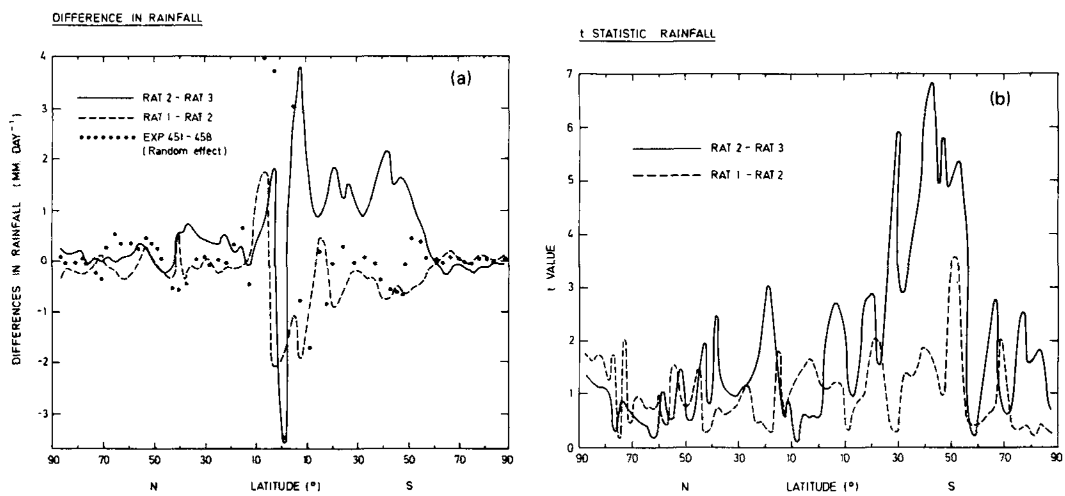

Fig. 5. (a) The changes in the zonally averaged rainfall as a function of latitude for the experiments. (b) The zonally averaged student "t"-test statistic for the difference in $RAT1–RAT2$ ----; $RAT2–RAT3$ ——.

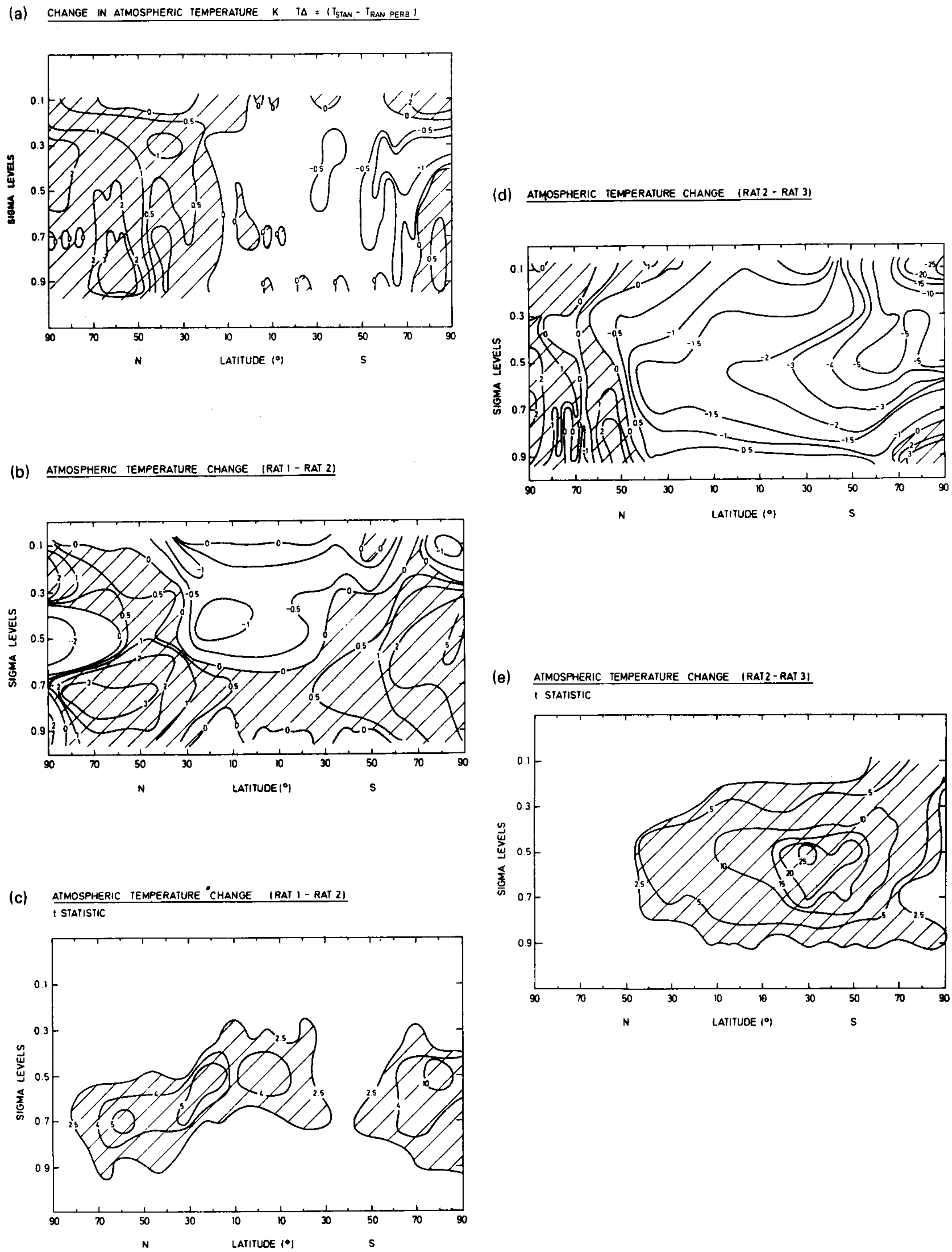

Fig. 6. The zonally averaged cross-section of atmospheric temperature as a function of latitude. (a) The random effect, (b) *RAT*1–*RAT*2, (c) *t* statistic for *RAT*1–*RAT*2, (d) *RAT*2–*RAT*3, (e) *t* statistic for *RAT*2–*RAT*3.

Table 4. *RAT experiments—atmospheric changes*

Temperature (K)	*RAT*1–*RAT*2 Change in position of cloud base: Change	*t*	*RAT*2–*RAT*3 Change in radiative properties: Change	*t*	Clim-rand. pert. Natural variation change
$\sigma = 0.1$	−0.19	0.08	−1.48	0.77	0.08
$\sigma = 0.3$	−0.15	0.58	−1.40	5.01	0.11
$\sigma = 0.5$	−0.12	1.03	−2.37	20.7	0.16
$\sigma = 0.7$	1.13	18.2	−1.45	22.5	0.21
$\sigma = 0.9$	0.42	6.3	0.0	0.4	0.4
u/V (m s^{-1})					
$\sigma = 0.1$	−1.3/0.0	2.74/1.81	−0.2/0.0	0.08/0.95	0.1/0.0
$\sigma = 0.3$	−0.8/0.0	2.6/0.23	−0.1/0.0	0.03/1.6	−0.1/0.1
$\sigma = 0.5$	−0.3/−0.1	2.03/0.82	−0.1/−0.0	0.02/1.8	−0.1/0.0
$\sigma = 0.7$	−0.0/−0.0	0.43/1.12	−0.2/0.0	1.43/0.01	−0.1/0.0
$\sigma = 0.9$	0.2/0.0	1.8/0.01	−0.2/−0.1	1.03/0.5	−0.0/0.0

4. Conclusions

The results of the general circulation model climatologies reported in this paper have been used to investigate their sensitivity to changes in the cloud structure and radiative properties. The conclusions from these studies may be summarized as follows.

(i) The model-generated climatology is more sensitive to changes in the cloud transmissivity from 0.35 to 0.15, and the absorptivity from 0.17 to 0.35, than to a lowering of the cloud base by 200 mb.
(ii) In the surface heat balance, these studies suggest that the most sensitive terms are evaporation, absorbed solar flux and the infrared net flux.
(iii) Changing the radiative properties produces global changes in surface temperature, rainfall, surface radiative balance and evaporation, which are possibly significant. The radiative changes in the model-generated climatology are particularly large in the southern summer hemisphere. Rainfall and evaporation changes occur primarily in the regions of 30–50° S and 30° N which result from the corresponding variations in the circulation patterns. Large changes are found in the atmospheric temperature structure in the region of ~30° N to 90° S.
(iv) Changing the position of the cloud base by 200 mb produces changes in the surface solar flux, surface radiative balance and atmospheric temperature structure.

These conclusions are not a direct indication of the behaviour of the atmosphere to these variations in cloud characteristics. We have tried to use a particular general circulation model to investigate the sensitivity of the model-generated climatology to certain prescribed changes in the cloud. In the current state of our knowledge, this may be the most productive way to use the models. The results indicate the importance of providing the cloud base and therefore its thickness as part of the global cloud climatology. The absence of details of the extent of the cloud prevents a unique description being made of the cloud representation in the model. Furthermore, these results stress the need for improved knowledge of the cloud radiative properties and for the development of methods that relate them to the cloud opacity generated by the model variables. Then with this improvement in our numerical models, we will be in a better position to carry out climate modelling experiments with more realistic cloud representations.

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REFERENCES

Chervin, R. M. and Schneider, S. H. 1976a. A study of the response of the NCAR GCM climatological statistics to random perturbations; estimating noise levels. *J. Atmos. Sci. 33*, 391–404.

Chervin, R. M. and Schneider, S. H. 1976b. On determining the statistical significance of climate experiments with general circulation models. *J. Atmos. Sci. 33*, 405–412.

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

Herman, G. F., Man-Li, Wu, C. and Johnson, W. T. 1980. The effect of clouds on the Earth's solar and infrared radiation budget. *J. Atmos. Sci. 37*, 1251–1261.

Hunt, G. E. 1975. A January climatology, zonal heat balance and cloudiness simulated by the Meteorological Office 5 level GCM. Meterorological Office, Technical Report No. 34.

Hunt, G. E. 1980. On the diurnal properties of clouds from geostationary satellite observations. In *Clouds, their formation, optical properties and effects* (eds. P. Hobbs and A. Deepak). Academic Press (1981) p. 281–315.

Manabe, S. and Wetherald, R. T. 1967. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *J. Atmos. Sci. 24*, 241–259.

Manabe, S. and Wetherald, R. T. 1975. The effects of doubling the CO_2 concentration on the climate of a general circulation model. *J. Atmos. Sci. 32*, 3–15.

McCleese, D. J. and Wilson, L. S. 1976. Cloud top heights from temperature sounding experiments. *Q.J. Roy. Met. Soc. 102*, 781–790.

Menzel, W. P., Schneider, A. J. and Smith, W. L. 1980. The CO_2 absorption method for applying cloud top pressures. In *International Radiation Symposium*, Fort Collins, 115–118 (Amer. Met. Soc.).

Minnis, P. and Harrison, E. F. 1980. A methodology for estimating cloud parameters from geostationary satellite infrared and visible data. In *International Radiation Symposium*, Fort Collins, 340–342 (Amer. Mat. Soc.).

Ohring, G. and Adler, S. 1978. Some experiments with a zonally averaged climate model. *J. Atmos. Sci. 33*, 2014–2020.

Rasool, S. I. and Schneider, S. H. 1971. Atmospheric carbon dioxide and aerosols: effects of large increases on global climate. *Science 173*, 138–141.

Saunders, R. W. and Hunt, G. E. 1980. The diurnal variation of the Earth's radiation budget measured by METEOSAT in *International Radiation Symposium*, Fort Collins, 329–332 (Amer. Met. Soc.).

Schneider, S. H. 1972. Cloudiness as a global climatic feedback mechanism: the effects on radiation balance and surface temperature of variations in cloudiness. *J. Atmos. Sci. 29*, 1413–1422.

Schneider, S. H., Washington, W. J. and Chervin, R. M. 1978. Cloudiness as a climatic feedback mechanism; effects on cloud amounts of prescribed global and regional surface temperature changes in the NCAR GCM. *J. Atmos. Sci. 35*, 2207–2221.

Shenk, W. E., Holub, R. J. and Neff, R. A. 1975. Stereographic cloud analysis from Apollo 6 photographs over a cloud front. *Bull. Amer. Met. Soc. 56*, 4–16.

Smith, W. L., Wolfe, H. M. and Haysen, C. M. 1973. Meteorological extractions from the NIMBUS 5 ITPR experiment Proc. "*Les Satellites Meteorologiques*", CNES Conf. Paris, 207–217.

Study of Man's Impact on Climate (SMIC) 1971. Inadvertant climate modification. Cambridge: MIT Press, 308 pp.

Vonder Haar, T. H. and Reynolds, D. W. 1974. A bi-spectral method for inferring cloud amount and cloud top temperatures using satellite data. *Sixth Conference on Aerospace and Aeronautical Meteorology*. Amer. Met. Soc., 190–194.

Vonder Haar, T. H. and Suomi, V. E. 1971. Measurements of the Earth's radiation budget from satellites during a five year period. Part 1. Extended time and space means. *J. Atmos. Sci. 23*, 305–314.

Winston, J. E. 1971. The annual course of zonal mean albedo as derived from ESSA 3 and 5 digitised picture data. *Mon. Weath. Rev. 99*, 818–827.