THE ROLE OF RADIATION IN THE ZONAL MEAN CIRCULATION: GCM EXPERIMENTS

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1. Introduction

The tendency of GCM's to drift towards a cold polar climate has been noted elsewhere in this report. This climate-drift is particularly serious in the winter polar stratosphere of the model. The model temperatures are colder than observed by 10-30°K (depending on the model) and the model polar night jet is typically twice as strong as observed. Several plausible sources for these deficiencies have been suggested in the literature including: lack of adequate vertical resolution; running the models with perpetual winter boundary conditions; inadequate treatment of subgrid scale processes in damping the waves and rigid upper boundary condition; (See also the discussion in O'Neill *et al.*, 1982). Based on these suggestions, several modelers have experimented with GCMs and such attempts have accomplished only limited success.

Recent GCM experiments at NCAR with a spectral general circulation model (Bourke *et al.*, 1977) seem to offer some insight into the possible reasons for the models' tendency to drift towards a cold pole. Upon introduction of a refined cloud/radiation model (described in Ramanathan *et al.*, 1982), the Bourke *et al.* (1977) model simulation of the zonal mean circulation improved significantly to the extent that its wintertime zonal mean winds were within 5 $m \cdot s^{-1}$ of the observed. The January and July simulations by this model are described in Pitcher *et al.* (1982). The cloud/radiation scheme is described in Ramanathan *et al.* (1982). The Ramanathan *et al.* paper also describes numerous GCM experiments. These experiments demonstrated that the improved simulation of the zonal mean winds by the GCM was primarily due to the refinements in

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the cloud/radiation model of Ramanathan et al. (1982). In the present paper, we present a brief summary of the results described in Ramanathan _et al._ (1982).

2. Description of the GCM

The spectral GCM is identical to the nine layer model described in Bourke _et al._ (1977) except for the prescription of orography and for the treatment of cloud radiation processes. The present model has an interactive cloud-radiation model. The clear sky radiation processes account for the effects of CO_2, H_2O and O_3.

3. Results of sensitivity experiments

The zonal mean temperatures and winds as simulated by the standard model for perpetual January conditions are shown in Fig. 1. The standard model is referred to as CONTROL. Upon comparing this simulation with that by Bourke _et al._ (1977), the basic difference is found in the region above 200 mb.

When the refinements (employed in the standard version) in the treatment of cloud/radiation processes were removed, the model simulation of the zonal mean circulation degraded (from the ones shown in Figure 1) significantly as shown in Fig. 2. This experiment referred to as DRVBC for "degraded radiation with various black cirrus". Fig. 2 mimics very closely the difficiences of most GCMs. It is important to note that the simulations shown in Figs. 1 and 2 were obtained from the same GCM except for the differences in the cloud/radiation treatment. To obtain Fig. 2, the cloud/radiation model used in CONTROL was degraded in the following manner:

(a) The temperature dependence of CO_2 longwave absorption (15 μm band) was ignored and furthermore the optical properties were chosen for a temperature of 300 K.

(b) The emissivity of cirrus clouds was assumed to be 1 (black cirrus) and clouds are allowed to form up to 150 mb. In the standard model, clouds are formed up to 250 mb from 0 to 45°, and poleward of 45° clouds are formed only up to 400 mb.

(c) The H_2O emissivity term was altered such that the consistency between H_2O emissivity and absortivity was not ensured.

(d) The upper boundary for solar and longwave calculations was changed from about 4.5 mb to the top of the atmosphere.

We show in Fig. 3, how the above four changes alter the zonal mean distribution of the net (solar plus longwave) radiative heating [Q], at time t = 0, i.e., the time when the changes were imposed for the DRVBC experiment. The ΔQ in Fig. 3, basically reflects the initial changes in the model radiative heating and Fig. 2 indicates the response of the model to the imposed changes. The four changes, (a) to (d), have different regions of influence:

(i) The omission of temperature dependence of CO_2 absorption (and adopting the optical properties for T = 300K) influences primarily the $\sigma = .009$ level (9 mb) and 0.074 level. Roughly 80% of the enhancement in the winter polar cooling [i.e., ΔQ = -.3°K/day] at the 9 mb level and 30% of the enhancement at 74 mb level are due to this effect.

(ii) The increased heating in the summer polar stratosphere (9 mb) is primarily due to the change in the boundary condition from 4 mb to

0 mb. As a result of this change, the O_3 solar heating in the mesosphere and upper stratosphere is unrealistically deposited at the 9 mb level.

(iii) 70% of the cooling in the polar lower stratosphere (74 mb) is due to the H_2O emissivity change. This change also mimics the following standard practice of GCMs: In the present model, for radiation calculations we use the H_2O mixing ratio (q) computed by the GCM. In most other GCMs, stratospheric H_2O is held fixed at 3 ppm (by mass). The present GCM computes a mixing ratio less than 1 ppm in the polar lower stratosphere. The difference in the H_2O longwave cooling between 3 ppm and 1 ppm is between 0.1 to 0.2 K/day. We believe it is inconsistent to prescribe 3 ppm H_2O when the model computed temperatures are less than 180 K. For example, at 74 mb, for $T \leq 180K$ and q = 3 ppm, the relative humidity is roughly 2000%!!

(iv) The upper tropospheric heating accompanied by strong polar cooling is primarily due to the inclusion of black cirrus clouds. The cirrus absorption of the warmer surface radiation causes a net heating in low-latitudes; however in the polar regions, since the surface emission drops significantly compared to that in the low latitudes, the cirrus emission is larger than its absorption of the surface radiation. Hence, the cirrus clouds cause a net radiative cooling of the polar upper troposphere. The downward emission by the cirrus causes a net heating in the region below the cirrus at all latitudes.

As seen from Fig. 3, the net effect of degrading the cloud/radiation model is to enhance the equator-to-pole gradient of radiative heating within the troposphere and to enhance the pole-to-pole gradient within the stratosphere. The 120-day average of the temperature difference (i.e., DRVBC minus CONTROL) is shown in Fig. 4a and is obtained by taking the difference of zonal mean temperatures shown in Fig. 1 and Fig. 2. Figs. 3 and 4a, clearly illustrate the sensitivity of zonal mean temperatures to alterations in radiative heating rate. Fig. 4b shows the results of another experiment which contains all of the changes as in DRVBC with one exception. In this experiment, the black cirrus clouds are prescribed and are referred to as degraded radiation with prescribed black cirrus (DRPBC).

It is beyond the scope of this paper to describe the detailed analysis of the model response to the imposed changes in cloud/radiation routines. We refer the interested reader to the paper by Ramanathan et al. (1982).

3. Concluding Remarks

A careful treatment of numerous radiative processes that control the meridional gradient in net radiative heating is a necessary condition for the proper simulation of the zonal mean temperatures and winds. The numerical experiments described here briefly and detailed in Ramanathan et al. (1982) clearly demonstrate that some of the problems causing the climate-drift in models arise from improper handling of the processes that control the meridional gradient of radiative heating. However, the observed winter polar stratospheric temperatures are maintained by a delicate balance between longwave radiative cooling and heating by dynamical processes. Hence, proper treatments of wave/mean flow interactions and the diabatic circulation (in addition to a careful treatment of radiation) are essential for capturing the observed wintertime circulation.

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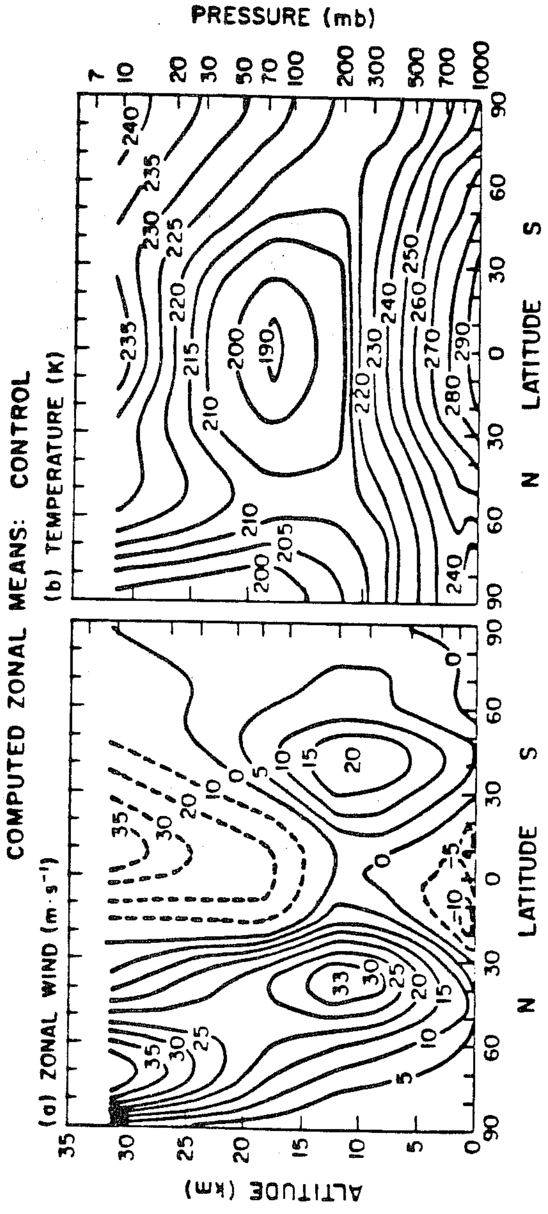
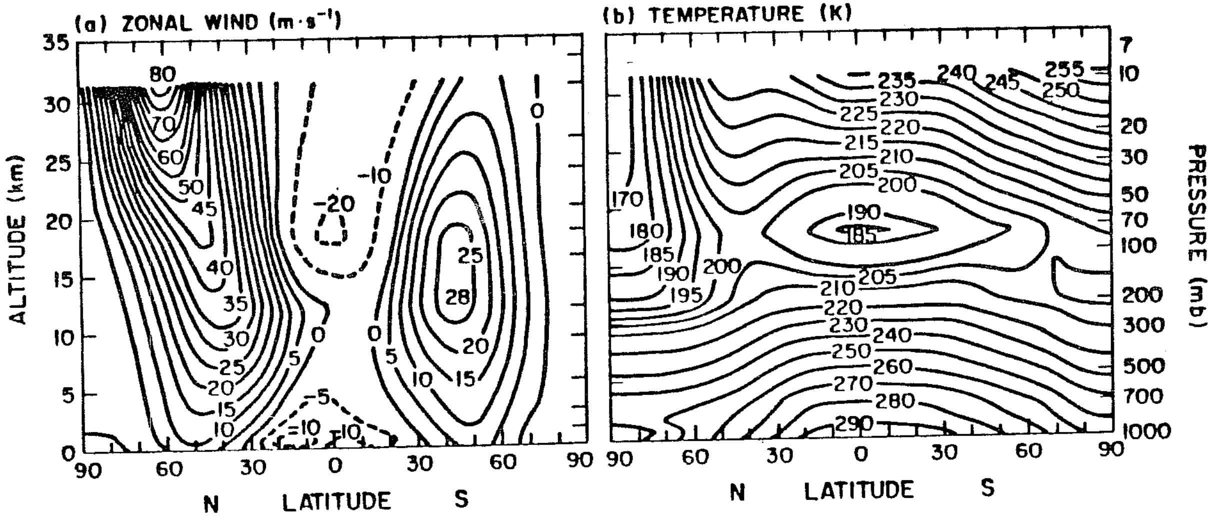

COMPUTED ZONAL MEANS: CONTROL
(a) ZONAL WIND (m·s⁻¹)
(b) TEMPERATURE (K)
ALTITUDE (km)
PRESSURE (mb)
35
30
25
20
15
10
5
0
7
10
20
30
50
70
100
200
300
500
700
1000
90
60
30
0
30
60
90
N
LATITUDE
S
35
30
25
33
30
25
20
15
10
5
0
35
30
20
10
0
5
10
15
20
0
-5
-10
240
235
230
225
220
215
210
200
190
205
210
220
230
240
250
260
270
280
290
240

Figure 1

COMPUTED ZONAL MEANS: DRVBC



DRVBC: Degraded radiation with variable black cirrus

Figure 2

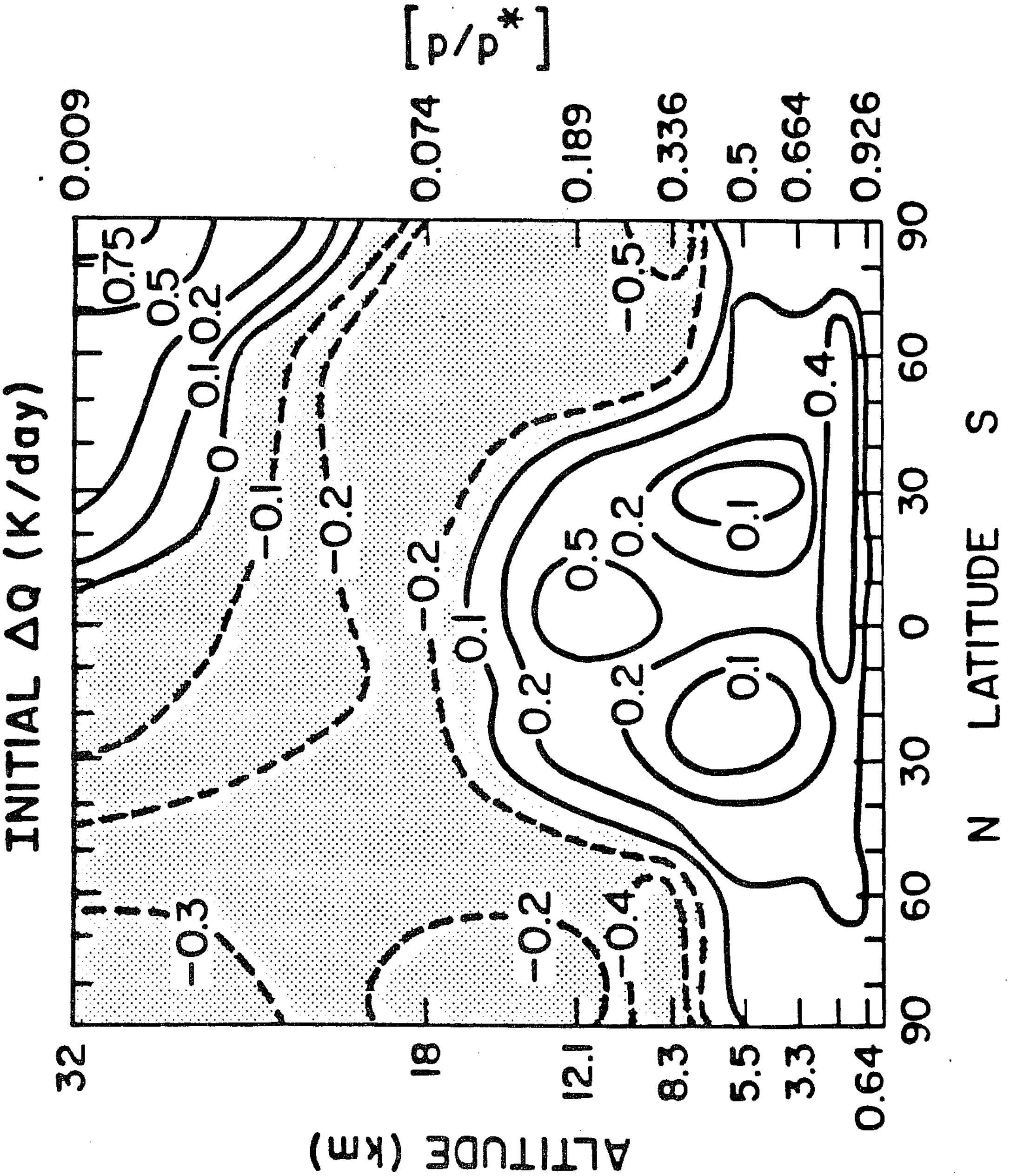
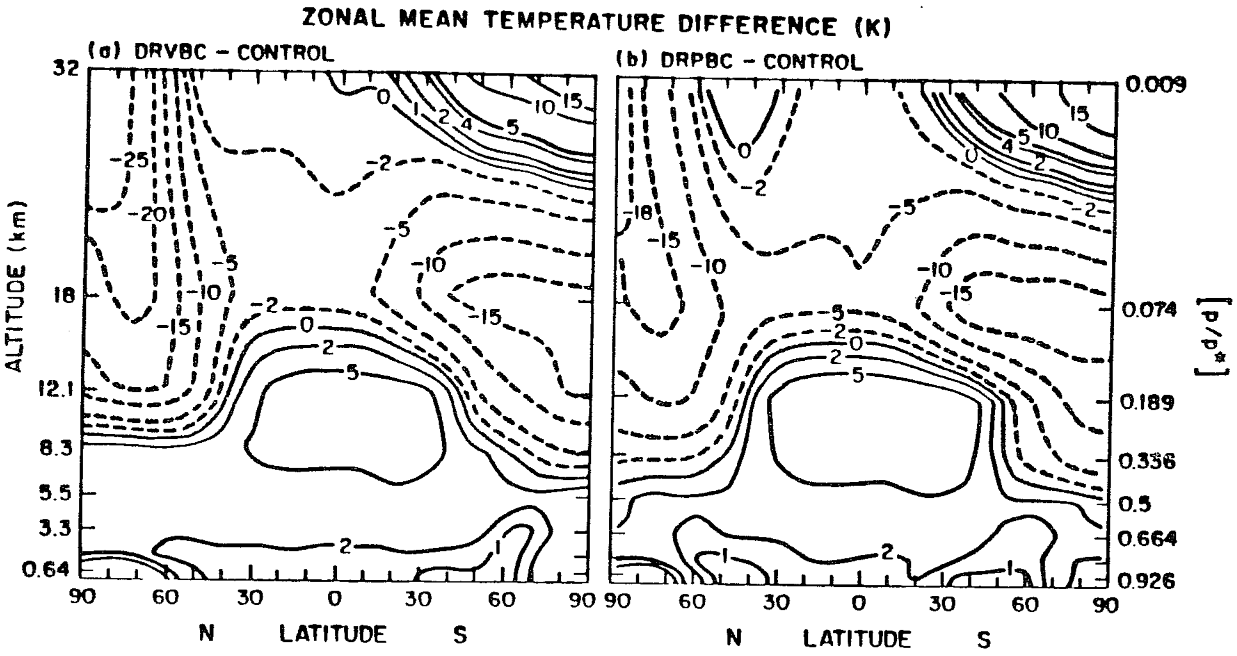

INITIAL ΔQ (K/day)
ALTITUDE (km)
32
18
12.1
8.3
5.5
3.3
0.64
[p/p*]
0.009
0.074
0.189
0.336
0.5
0.664
0.926
90
60
30
0
30
60
90
N LATITUDE S
0.75
0.5
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0.1
0.2
0.5
0.4

Figure 3



DRVBC: Degraded radiation with

variable black cirrus

DRPBC: Degraded radiation with

prescribed black cirrus

Figure 4