

*Progress Report on*  
**Assessing the Climatic Effect of  
Carbon Dioxide and Other Trace Gases Using an  
Interactive Two-dimensional Climate-Chemistry Model**

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This report covers work on grant DE-FG02-86ER60485 and consists of two parts: (1) progress for the period 12/1/92-5/31/93 and (2) the work plan for the remaining period 6/1/93-11/30/93. The project includes four tasks, two of which are addressed in the first project year: "Model Interface" and "Climate Sensitivity".

## I. PROJECT PROGRESS (12/1/92-9/30/93)

### *Task 1. Model Interface*

1) The AER Seasonal-Radiative-Dynamical (ASRD) climate model has lower meridional resolution than the chemistry model. The logical first step in interfacing the two components is to modify the ASRD model to allow for a higher meridional resolution (19 latitude bands). A literature search lead us to conclude that only the model's atmospheric meridional heat transport (MHT) scheme needs to be updated in a substantial way.

In the high-resolution version of the ASRD climate module, referred to as HASRD, we will use separate parameterizations for MHT in the mid-high latitudes and in the tropics. *In the mid-high latitudes*, atmospheric heat transport is dominated by large scale eddies. We have carried out preliminary experiments to evaluate and compare different parameterization schemes using the ASRD. It appears that the scheme developed by Stone (1974) and modified by Peng et al. (1982), which is based in part on the Eady (1949) model and in part on the two-layer model (Holton, 1979), simulates the MHT most realistically. Therefore we will adopt this scheme in our model.

*In the tropics*, eddy heat transport is much less important than the Hadley cell transport. Unfortunately, theoretical basis for parameterization of Hadley cell heat transport is not well established. The only scheme used in practice is that developed by Peng et al. (1987), which is based on the theoretical results of Held and

Hou (1980) and the empirical study of Rennick (1977). Its simulation of tropical heat transport compares well to the observation. We will adopt Peng et al.'s scheme in our model, and combine it with moist adiabatic adjustment, which is a good approximation for the tropical atmosphere (Stone and Carlson, 1979).

During this reporting period we also collected the necessary higher-resolution input data sets to prepare the corresponding input data fields for the HASRD. Implementation of coding changes required by the increased model resolution also has started.

(2) We decided that the coupling of the two modules will follow the following principle: prognostic variables from a given sub-model (climate or chemistry modules) that are needed to drive and/or provide initial conditions for the *other* module will be exchanged between the modules. This way, either the chemistry module can be run with the climate module as a "subroutine/black box" (*i. e.*, diagnostics not needed for the evaluation of chemistry model performance will be suppressed) providing an interactive tropospheric boundary, or the climate module can be run using the chemistry module's changing stratospheric temperatures and trace gas composition to determine the troposphere-surface climate system forcing.

During this reporting period we also have completed our paper on ozone-depletion climatic effects and submitted to *Nature* (Molnar *et al.*, 1993, see as Appendix A).

## *Task 2. Climate Sensitivity*

### Task 2a. Role of Tropical Convective Adjustment

We have started to assess how the choice of tropical convection parameterization affects the response to CO<sub>2</sub>-doubling. For the moment, we performed simulations using the "standard" 6.5 K/km and moist-adiabatic lapse rates (with boundary-layer parameterization added), as well as employing a cumulus-convection parameterization (Lindzen *et al.*, 1982; Satoh and Hayashi,

1992) in the tropical zone. The latter is the most interactive, because the vertical temperature structure is not governed by a prescribed lapse rate. We found (Fig. 1) that although the surface temperature changes are similar for moist adiabatic lapse rate and cumulus parameterizations for tropical conditions, the cumulus convection scheme provides the largest mid-tropospheric warming, whilst the moist adiabatic adjustment leads to the largest warming in the upper troposphere. These results have significant implications regarding the water vapor feedback, because warmer atmospheric layers can hold more moisture.

#### Task 2b. Cloud Optical Property Feedbacks

We have implemented the Platt and Harshwardhan (1988) cirrus optical thickness parameterization into the code. Preliminary experiment results (when only the tropical oceanic cirrus was parameterized this way) imply that, at least for the current climate, our choice of cirrus visible optical depth of 2 (at 0.55  $\mu\text{m}$ ) is appropriate.

#### Task 2c. Tropical Cloudiness/Sea-Surface Temperature(SST) Feedbacks:

We continued to use the ASRD model to study the effects of low-latitude oceanic cloud/climate feedbacks in relation to trace gas increases. For the warmest SSTs, ERBE measurements indicate that over the oceans the greenhouse trapping (difference between longwave radiance emitted to space,  $F$  and surface black-body radiance,  $E$ ) increases sharply with rising SST (Raval and Ramanathan, 1989; Duvel and Breon, 1991; Ramanathan and Collins, 1991, referred to as RC91 in the rest of the text; Stephens and Greenwald, 1991; Ackerman et al., 1992; Kiehl and Briegleb, 1992; Hallberg and Inamdar, 1993). Defining the "Greenhouse Parameter"  $G$ , as  $\Delta(E - F)/\Delta\text{SST}$ , an apparent "super greenhouse effect" may be inferred, for instance, from Fig. 2a of RC91, indicating that over most of the tropical ocean ( $\text{SST} > 297\text{-}300\text{K}$ ),  $G$  becomes very large (about  $17\text{-}25 \text{ Wm}^{-2}\text{K}^{-1}$ ) compared to regions with lower SST values. The "cirrus thermostat" is RC91's assertion that this super greenhouse effect will be limited by formation of highly reflective cirrus clouds, shielding large amounts of solar radiation, limiting SST to temperatures no greater than about 305K.

Fu *et al.* (1992) questioned the existence of the cirrus thermostat, and argued in favor of evaporative (surface latent) heat flux changes acting as a "thermostat". Additional, independent cloud statistics presented by Waliser *et al.* (1993) was interpreted as making the case both for (according to Ramanathan and Collins, 1993) and against (according to Fu *et al.*, 1993) the cirrus thermostat hypothesis. Most recently, Waliser and Graham (1993) further studied this problem and found that the relative importance of solar (cloud reflection) forcing appears to be stronger than evaporative cooling mechanisms in determining the observed upper limits in tropical SST. These studies prompted us to expand our previous numerical investigations (Molnar and Wang, 1990; Molnar, 1993—see the latter as Appendix B) regarding the potential role of tropical oceanic cloud feedbacks during greenhouse warming. In particular, we addressed which of the above-mentioned two effects are more likely to be responsible for governing SST changes that accompany CO<sub>2</sub> doubling.

In principle, both cloud properties and evaporative surface heat fluxes (and wind speed which strongly influences the latter) may change during greenhouse warming. Lacking parallel observations of oceanic cloudiness and trace gas concentration increases (because trace gas concentrations have changed too little during the at most few years time span of useful satellite observations) we had to be content with implementing the Weare (1992) satellite-based tropical oceanic cirrus properties—SST relationships (associated with anomalies of the current climate) into the AER climate module. These newer satellite cloud analyses appear to be more representative to tropical high cloud behavior *on large scale* (encompassing the *whole* tropical ocean) than the Fu *et al.* (1990, 1992) studies we used before, so reevaluation of the potential effect of cirrus changes during CO<sub>2</sub>-doubling seems warranted). This time, in addition to cirrus fraction changes, we also used Weare's findings to relate SST changes to cirrus altitude changes.

The role evaporative fluxes was assessed by simply performing our climate sensitivity tests with and without interactive latent heat flux changes. In the latter case we fixed surface latent heat fluxes at their control climate values (such cases are referred to as *FLH*). Furthermore, following T. P. Barnett's suggestion (personal communication—1993) we also investigated what role the CO<sub>2</sub>-doubling induced tropical surface wind-speed changes may play in answering the cloud forcing

versus evaporation question. Since wind speed is not a prognostic variable in our model, we used results from two "representative" General Circulation Model (GCM) simulations, one showing a significant tropical wind-speed *increase* (GISS GCM), whilst the other a *decrease* with a smaller magnitude (GFDL GCM).

In the followings we highlight the results of some of the 16 experiments performed. Table 1 lists the selected experiments discussed briefly here. In the table  $A_c$  and  $Z_c$  denotes cirrus cloud fractional cover and cloud top height, respectively, whilst  $\beta$  refers to the ratio of cirrus ice particle shortwave scattering efficiency and longwave absorption efficiency. In the "standard" model state the cirrus ice particles are assumed to have large (around 25  $\mu\text{m}$ ) mean radius and  $\beta$  is prescribed at the value of 2. However, as deep convective activity increases (with increasing SST), the colder anvil cirrus produced may contain smaller ice particles with much larger  $\beta$  values (Heymsfield and Miloshevich, 1991). We tested this assumption by increasing  $\beta$  to 4, corresponding to a mean particle radius of about 6  $\mu\text{m}$ , thus increasing cirrus reflectivity.

Table 2 summarizes our findings showing the tropical oceanic Greenhouse Parameter introduced above together with the corresponding surface air ( $T_s$ ) and SST ( $T_g$ ) responses as well as latent heat flux changes. The results illustrate that increase of cirrus fractional cover and cloud top height with increased deep convection could induce either a strong positive *or* a negative feedback *for SSTs*, depending on cirrus microphysical properties, represented simply by  $\beta$  in this study. In particular, large cirrus particles would lead to a strong positive feedback (see  $T_g$  for case #2), whilst small cirrus particles ( $\beta=4$ ) induce a negative feedback (see  $T_g$  for cases #4, #14).

The results also indicate that evaporation changes alone, or even in combination with (GCM-)predicted wind speed changes, cannot put the model-computed  $G$  close to its observed range. Only the  $\beta$  parameter seems to be able to affect  $G$  appreciably, making it compatible with the observed overall greenhouse slope prevailing at the SSTs occurring after  $\text{CO}_2$  doubling.

Interestingly, *for the surface air temperature* we always obtain a larger response than for the "standard" case. This finding appears to bear significance in

rela relation to a quite different issue: an important part of the instrumental "surface ten temperature" record *is* actually SST, and it is combined with land surface *air* ten temperatures to provide a *global mean* "surface temperature" time series. Our sen sensitivity experiments clearly illustrate that a small measured SST trend could act actually hide a large surface air temperature trend (and all this may happen even wit without interactions with the deep ocean). For instance, if cirrus indeed became mo more reflective and wind speed increased as predicted by the GISS GCM (see Exp Experiment #14 in Table 2), SST would increase only about half as much as for the "sta "standard" CO<sub>2</sub> doubling case, whilst  $T_s$  would actually increase a little bit more. Sim Similar situation occurs for cases #4 and #11. Unfortunately, this may mean that the the whole available instrumental record based trend (cf. ISCCP, 1990) of pos postindustrial *global mean* surface temperature increase may contain much larger err errors than previously thought, to the extent that it cannot be used to infer whe whether greenhouse warming has been occurring or not. This problem does not eve even appear to be correctable since longer-term surface air temperature me measurements over oceans are either missing or are very unreliable (cf. ISCCP, 199(1990)).

A manuscript is currently being prepared on these matters for journal sub submission.

## II. II. FUTURE PLANS (10/1/93-11/30/93)

### *Task Task 1. Model Interface*

- (1) (1) We plan to complete the HASRD development during the next quarter.
- (2) (2) Interactive coupling will be accomplished by the end of the project year.

### *Task Task 2. Climate Sensitivity*

#### Task Task 2a. Role of Tropical Convective Adjustment

1) We will continue to study the effects of different large-scale parameterizations of tropical deep convection in the context of CO<sub>2</sub>-doubling. For this comparison we plan to use:

- "standard", 6.5 K/km lapse-rate adjustment,
- moist-adiabatic lapse-rate adjustment,
- the cumulus-convection parameterization of Lindzen et al. (1982), and
- the Emanuel (1991) scheme (the latter will be addressed in the second project year).

#### Task 2b. Cloud Optical Property Feedbacks

Using the ASRD climate module, during the first project year we will evaluate -in the context of CO<sub>2</sub>-doubling-, the effects of the Betts and Harshwardhan (1987) and Platt and Harshwardhan (1988) cloud optical thickness parameterizations.

#### Task 2c. Tropical Cloudiness/SST Feedbacks:

- 1) Prepare a paper for journal submission on the "cirrus-thermostat" hypothesis.
- 2) Using the results of completed (published) and ongoing research, we will seek relationships between SST and Marine Stratiform Cloudiness properties, and we will implement these relationships into the ASRD climate module to assess the role of these empirically inferred feedbacks during greenhouse warming.

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## Figure Captions

*Figure 1.:* Model Calculated Temperature Profile Changes due to CO<sub>2</sub>-Doubling for the Tropical Zone.

# Tropical Temperature Changes due to CO<sub>2</sub> Doubling

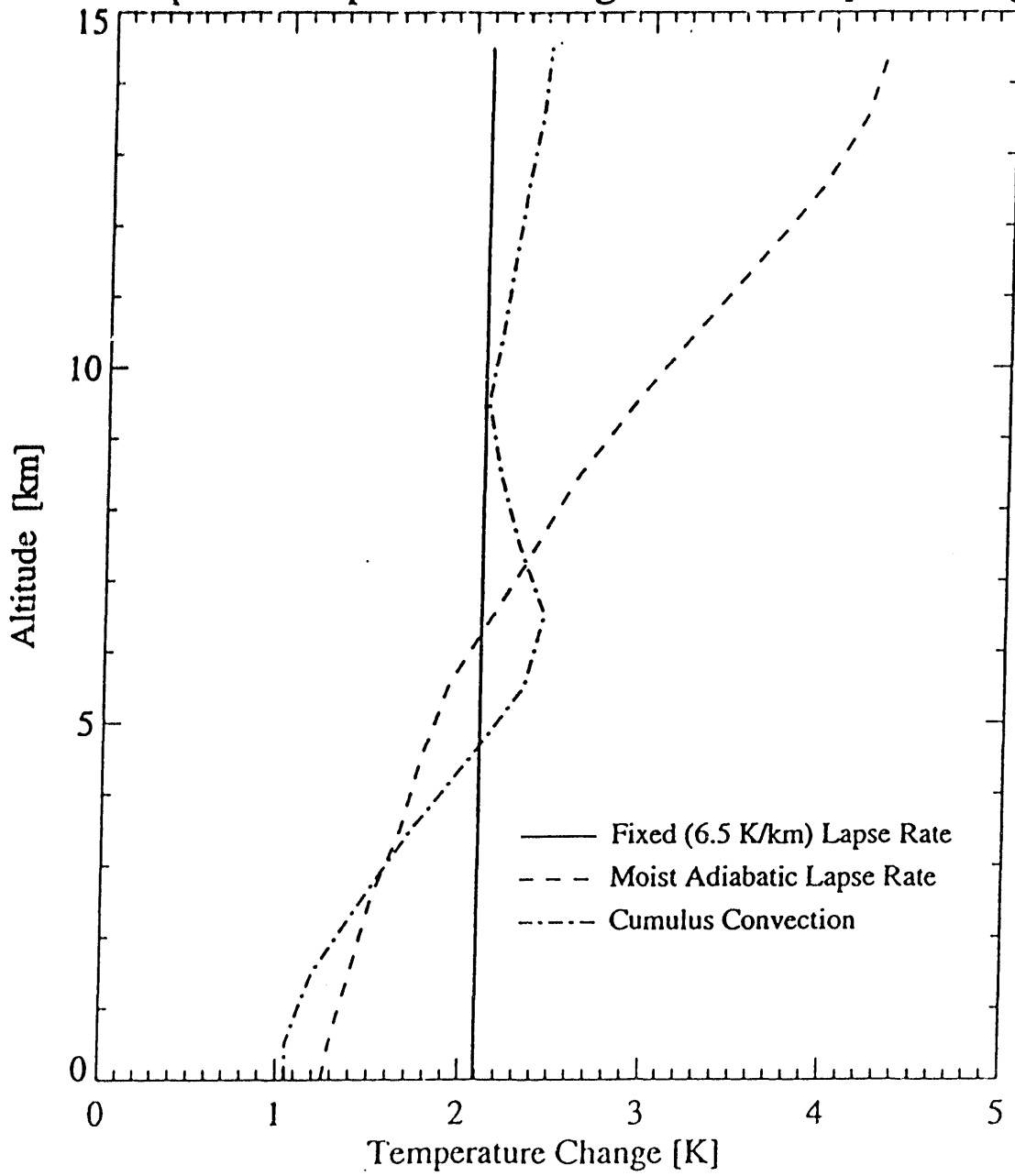


Figure 1.

**TABLE 1. SUMMARY of SELECTED CLOUD FEEDBACK EXPERIMENTS.**

- # 1: "Standard"  $2\times\text{CO}_2$ ; *i. e.* no cloud feedbacks;  $\beta=2$
- # 4:  $2\times\text{CO}_2$ ;  $A_c\&Z_c$ -SST FDKs (Weare);  $\beta=4$
- # 5:  $2\times\text{CO}_2$ ;  $A_c\&Z_c$ -SST FDKs (Weare);  $\beta=2$
- #11:  $2\times\text{CO}_2$ ;  $A_c\&Z_c$ -SST FDKs (Weare);  $\beta=4$ ; FLH
- #12:  $2\times\text{CO}_2$ ;  $A_c\&Z_c$ -SST FDKs (Weare);  $\beta=2$ ; GISS (%) wind-speed change
- #14:  $2\times\text{CO}_2$ ;  $A_c\&Z_c$ -SST FDKs (Weare);  $\beta=4$ ; GISS (%) wind-speed change
- #15:  $2\times\text{CO}_2$ ;  $A_c\&Z_c$ -SST FDKs (Weare);  $\beta=4$ ; GFDL (%) wind-speed change

**TABLE 2. ANNUAL MEAN EVALUATION of SELECTED CLOUD FEEDBACK EXPERIMENTS.**

# 1:	$\Delta T_s=1.25$	$\Delta T_g=1.04$	$G= 4.90$	$\Delta\text{FLH}= 4.59$
# 4:	$\Delta T_s=1.47$	$\Delta T_g=0.95$	$G=17.49$	$\Delta\text{FLH}= 0.44$
# 5:	$\Delta T_s=1.93$	$\Delta T_g=1.50$	$G=10.37$	$\Delta\text{FLH}= 5.15$
#11:	$\Delta T_s=1.48$	$\Delta T_g=0.99$	$G=17.37$	$\Delta\text{FLH}= 0.00$
#12:	$\Delta T_s=1.87$	$\Delta T_g=1.12$	$G=10.43$	$\Delta\text{FLH}= 8.69$
#14:	$\Delta T_s=1.30$	$\Delta T_g=0.53$	$G=20.54$	$\Delta\text{FLH}= 4.22$
#15:	$\Delta T_s=1.51$	$\Delta T_g=1.07$	$G=17.09$	$\Delta\text{FLH}= -0.57$

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