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Progress Report on Natural and Anthropogenic Climate Change

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This report covers work on grant DE-FG02-86ER60485 and consists of two parts: (1) progress for the period 9/1/91-3/31/92 and (2) the plan for the remaining period 4/1/92-8/31/92. The project includes two tasks: atmospheric radiation and improvement of climate models to evaluate the climatic effects of radiation changes. We have been performing this work in cooperation with our project subcontractor, Atmospheric Sciences Research Center, State University of New York, Albany (Professor W.-C. Wang, Principal Investigator).

I. PROJECT PROGRESS (9/1/91-3/31/92)

Task 1: Atmospheric Radiation

This task includes four subtasks: (1) Intercomparison of Radiation Codes in Climate Models (ICRCCM), (2) analysis of the water vapor continuum using line-by-line calculations to develop a parameterization for use in climate models, (3) parameterization of longwave radiation and (4) climate/radiation interactions of desert aerosols. Our effort in this period is focused on the first three subtasks.

Subtask 1: ICRCCM

Interaction with the ICRCCM community has been active principally with respect to the line-by-line calculation of spectral fluxes and longwave cooling rates for water vapor. W. Ridgway, associated with the Goddard Laboratory for Atmospheres (GLA) and coordinator of the line-by-line aspect of ICRCCM, is currently performing spectral comparisons of our flux and cooling rate results with those of the other participants. Plans continue to be under discussion with respect to archiving the spectral results from the various participants. Table 1 provides a comparison of the spectrally integrated results from our model and the GLA model for four of the ICRCCM water vapor exercises. The principal differences between the models are attributable to differences in the water vapor continuum. The water vapor continuum model used for these calculations is available on disk or over Internet to ICRCCM participants and the general science community.

Subtask 2: Water Vapor Analysis

The focus of the research effort for this subtask during this reporting period has been concentrated on the implications of our cooling rate calculations for water vapor. A number of significant results have resulted from this effort and are described in a paper submitted to *JGR-Atmospheres*: (1) Spectral cooling rates provide a strong correlation between spectral region and altitude of maximum cooling; (2) The pure rotation region (10-800 cm-1) is the dominant spectral region for

TABLE 1. Comparison of the Fluxes from the Present Models (mAER and AER) and the GLA Model for the Surface (SFC), the Tropopause (TROP; Indicated Pressure Level) and the Top of the Atmosphere (TOA). Units are W m^{-2}

Cases	Flux Model	SFC↑	SFC↓	TROP↑	TROP↓	TOA
(179 mb)						
Mid-Lat. Summer	mAER	423.3	269.0	335.8	6.9	335.7
(No Continuum)	mAER-GLA	-0.2	1.7	-0.8	-0.6	-0.8
(179 mb)						
Mid-Lat. Summer	AER	423.3	333.8	321.3	7.4	321.1
	AER-GLA	-0.2	3.2	-7.1	1.1	-7.2
94 mb						
Tropical	AER	458.9	385.9	332.3	3.1	332.6
	AER-GLA	-0.2	2.0	-6.5	0.5	-6.5
(276 mb)						
Sub-arctic Winter	AER	247.6	138.2	222.4	16.2	221.5

atmospheric cooling due to water vapor; and (3) the contributions to the outgoing spectral radiance are highly correlated with spectral cooling rate. These results suggest that for radiative forcing due to water vapor, greater significance should be placed on the far longwave spectral region and that spectral observations from space can provide an excellent diagnostic of process performance in GCM's.

An important difference in our results for water vapor and those previously reported is the effect of the foreign broadened continuum (p-type). This continuum contributes increased atmospheric opacity between the spectral lines in the strongly absorbing regions, particularly in the 250 350 cm^{-1} region. This results in increased cooling in the important upper troposphere regime, amounting to 0.4°K per day or 20% for the mid-latitude summer atmosphere. In addition to these results we have studied the effects of atmospheric refraction and earth sphericity on tropospheric flux calculations. For the spectral region and altitude regime studied, the effects were found to be negligible. Our calculations under this effort have been greatly facilitated by the availability of a vectorized line-by-line model derived from FASCODE. This model was developed under an ARM grant to AER, (grant no.DE-FG02-90ER61064). The water vapor calculations for 0-3000cm^{-1} with three quadrature values for the fluxes presently require ~6 minutes on the CRAY-ymp. This represents an improvement of approximately a factor of twenty, enabling more extensive calculations for a fixed cost.

Subtask 3: Parameterization of Long Wave Radiation

This subtask is performed by Professor W.-C. Wang at the State University of New York at Albany. The refinement of the parameterization of the long wave radiation in the study of atmospheric greenhouse gases is being continued. The focus is on the use of a uniform approach to treat the gaseous absorption in the atmosphere as well as the multiple scattering due to particles. The broad band k-distribution formulation and the most updated atmospheric absorption line compilation prepared by the AFGL are used. Currently, we are working on the parameterization of the broad band water vapor continuum absorption.

Task 2: Modeling Climate Effects of Radiation Changes

The task includes two subtasks : GCM study and 2-D model development and application.

Subtask 1: GCM Study

This subtask is performed by Professor W.-C. Wang at the State University of New York at Albany. During this period, we continue the contribution to two documents: the 1991 UNEP Ozone Assessment Report and the 1992 IPCC Supplemental Report. For the first document, we have carried out additional calculations of the radiative forcing due to increase of atmospheric CO_2, CH_4, N_2O, and CFCs and the observed stratospheric O_3 depletion. For the second document, we have provided results of general circulation model simulated "enhanced" greenhouse effect. In the meantime, we also serve as reviewer for both documents.

Subtask 2: 2-D Seasonal Model Development and Applications

A. Climate Sensitivity Experiments

(a) The role of dynamical heat transport in stabilization of the climate response to changes in solar luminosity

Recent interest in global change has revived interest in understanding paleoclimates as indicators of climate variability. One of the major puzzles of Earth history is that the global average surface temperature has been fairly constant over geologic time scales (within about 10°K of the current value) even though solar luminosity was as much as 20-30% lower 4 billion years ago, according to established knowledge about stellar evolution (e.g., Newkirk, 1980).

Using a 2-dimensional (latitude-height) annual mean model of the Northern Hemisphere, Molnar and Wang (1984) have shown that dynamical heat flux feedbacks associated with vertical heat transport (VHT) and meridional heat transport (MHT) can stabilize global temperatures with respect to solar luminosity decreases. As a follow-up study, during the last project year we used the AER 2-D Seasonal Radiative-Dynamical (ASRD) model to illustrate that the feedback mechanisms associated with VHT and MHT can help to maintain a stable climate, resisting runaway glaciation. The seasonal model's global stability values are somewhat similar to those found in our previous annual model study (Molnar and Wang, 1984). The most notable difference between the annual and seasonal model results is the larger global stability in the annual fixed MHT case. At the same time, the seasonal model's response is much more gradual than the annual model's. The model results suggest that the dynamical heat flux feedbacks alone could have played an important role in maintaining a rather high global stability value against total glaciation over most of the geological time scale.

These results were presented at the *Fifth Conference on Climate Variations*, Oct. 14-18, Denver, CO (Molnar and Gutowski, 1991). An extended version is currently being prepared for submission to *Ann. Glaciol.*, the journal where our annual model work was published.

(b) The role of atmospheric meridional heat transport in climate response to changes in moisture content

Differences in parameterization of atmospheric meridional heat transport may lead to significantly different responses of the climate system to radiative forcing. The role of atmospheric MHT could be very significant in determining the latitudinal dependence and magnitude of a climate response to parameterization in radiative forcing (e. g., North et al. 1981; Stone and Risbey, 1990). We continued to explore the difference between the "physical' (Stone and Yao, 1989) and "empirical" (Wang et al., 1984) MHT parameterizations in determining model climate sensitivity.

This time, we examined the climatic consequences if the mechanism proposed by Lindzen (1990) was operating in the model's tropical zone. Lindzen (1990) argued that an increase of deep-convection intensity (the mass flux in tropical convective clouds) accompanying the predicted greenhouse warming may lead to a decrease of water vapor content of the tropical middle and upper troposphere. He also suggested the decrease in moisture content in the tropics may act as a negative feedback and severely limit the greenhouse warming on a global scale. We examined the response of the climate system by performing a CO_2-doubling experiment and requiring the tropical moisture content above about 4km in the model to decrease with increasing tropical SST. Our results showed that the suggested adjustment of tropical moisture content could negate the warming in the tropics. However, compared to the 'standard' CO_2-doubling case, the surface temperature increase at the higher latitudes diminishes only by about 20% with the physical MHT parameterization, and by 40% with the empirical parameterization. These results suggest that a better understanding of meridional heat transports is necessary. We plan to further explore the cause of these differences and publish the results in the near future.

(c) Cloud/climate feedbacks

We continued to use the AER-SRD model to study the effects of low-latitude oceanic cloud/climate feedbacks in relation to trace gas increases.

One of the greatest uncertainties about future climate changes is associated with the behavior of clouds in response to climate perturbations (e. g., WMO 1987). Cloud/climate interactions could be especially pronounced in the low-latitude regions where solar insolation and sea-surface temperature (SST) are high all year round. Consequently, model studies of the surface warming due to the projected increase of atmospheric greenhouse gases should take into account possible changes in tropical cloud properties accompanying the greenhouse warming. For instance, ERBE measurement analyses (Raval and Ramanathan, 1989; Ramanathan and Collins, 1991, referred to as RC91 in the rest of the text) indicate the possible presence of an apparent "runaway greenhouse" on one hand and a "cirrus limiting factor" on the other. The "runaway greenhouse effect" is a positive feedback that is speculated to occur when the increase in SST leads to increase in moisture content. The "cirrus limiting factor" is RC91's assertion that this "runaway greenhouse" will be limited by formation of highly reflective cirrus clouds, shielding large amounts of solar radiation, limiting SST to temperatures no greater than around 305°K.

Using the ASRD model, we have investigated what the implications of these results might be in the context of enhanced radiative forcing from accumulation of greenhouse gases. We performed a series of CO_2-doubling experiments with tropical oceanic deep convective cloudiness (DCC) and especially cirrus changes, and analyze the key greenhouse indicators over the tropical ocean. Our results indicate that with the fixed relative humidity and moist adiabatic lapse rate assumptions, increases in SST would induce increases in water vapor . On the other hand, our results also showed that increase of cirrus fractional cover with increased deep convection could induce either a strong positive *or* a strong negative feedback, depending on cirrus microphysical properties. In particular, large cirrus particles could lead to strong positive feedback, whilst small cirrus particles correspond to an appreciable negative feedback strength. The influence on the extratropics is related to the efficiency of the meridional heat transport.

These results emphasize the importance of equatorial measurement programs such as TOGA/COARE, and the importance of more accurate in situ and satellite cloud measurements, which, among other things, will provide a more accurate DCC, cirrus properties, and SST climatology. Part of the above described cloud-feedback investigations was presented at the 20th General Assembly of the International Union of Geodesy and Geophysics in Vienna, Austria, Aug. 12-24, 1991. A manuscript is currently being prepared on this matter for journal submission.

Another issue of interest is the effect of increases in cirrus cover due to operation of aircraft. Contrails of subsonic flights appear to be increasing in frequency, to the point that their climatology can be compiled (DeGrand et al. 1990). In principle, jet contrails could augment the area and optical thickness of existing cirrus, or they may promote the formation of independent "contrail-cirrus" clouds. By analogy, operation of supersonic aircraft in the lower stratosphere could also lead to increases in high cirrus or lower stratospheric clouds.

The AER-SRD model was applied for two studies.

i) A first order assessment of the importance of contrail cirrus in the troposphere. We increased the cover and optical thickness of existing cirrus in 30-60°N latitude belt by 20% and 30%, respectively, thus simulating the effect of increasing subsonic traffic as well as possible seeding from supersonic aircraft. This perturbation caused a warming of the size about 50% of the CO_2-doubling signal for the 30-90°N zone.

ii) We added lower stratosphere clouds with a 10 % fractional cover and a shortwave optical thickness of 1.0 into the 19-22 km layer of the 30-90°N latitude belt. This change prompted a warming as large as about 140% of the CO_2-doubling signal for the same zone. Further experiments revealed that a mere 3% fractional cover of cirrus lower stratospheric clouds could cause the same effect as the large perturbations of existing cirrus mentioned above.

B. Climate-Chemistry Interactions

(a) Closed-loop model set-up

Current projections indicate that by the middle of the next century the earth's climate will be considerably different from that of today, due to increasing concentrations of trace gases with greenhouse potential (e.g., IPCC, 1990). During this same time period, these and other human activities (stratospheric aircraft, etc.) may have a significant impact on ozone distribution in the lower stratosphere and upper troposphere. Thus, predictions of changes in trace gas concentrations, particularly that of O_3, have to depend on photochemical models. Thus it seems necessary to develop fully coupled climate/chemistry models.

2-D Interactive Climate-Chemistry Models (ICCMs) may fill an important gap to address potentially important climate-chemistry interactions for the coming decades. We started to develop such a model at AER. In its current form, the 2-D ICCM consists of two interactively coupled submodels: the AER 2-D SRD model and the AER 2-D dynamical-chemical-radiative model (Schneider et al., 1989). In practice, the climate model tropospheric heating rates will be fed as lower boundary conditions for the chemistry model. At the same time, the climate model treats the chemistry model as a "stratospheric forcing" term.

(b) Climatic consequences of the observed ozone loss during the last decade: relevance to the greenhouse problem

Observations reported recently by the United Nations (1991) indicated significant ozone losses over the past ten years below (approximately) 25 km level in nearly all seasons. Previous radiative radiative forcing calculations (Wang et al, Wang and Sze), showed that ozone decrease above 25 km tends to somewhat augment the greenhouse forcing, whilst decrease below 25 km has the opposite effect.

We started a study to use the AER-SRD model to quantitatively assess the possible climatic significance of these observations, by calculating the surface temperature changes explicitly. We are in the process of performing climate perturbation experiments to determine surface temperature distribution differences between 1979 and 1990 with and without the observed ozone depletion.

II. FUTURE PLANS (4/1/92-8/31/92)

Task 1:

For this task, the effort in the concluding phase of the grant will be directed to the line-by-line calculation of longwave radiative forcing due to carbon dioxide and the trace gases including the CFC's and the change in that forcing due to the anticipated changes in the abundances of the trace greenhouse gases over the past ten year period. These calculations will be performed for two latitudes: tropical and upper-midlatitude. For the latter both a summer and winter profile will be utilized. The objective here is to obtain a global estimate of flux and cooling rate changes for the clear sky due to the 10 year change in atmospheric molecular abundances. These calculations will be line-by-line calculations using the CKD water vapor continuum. Specific physical issues to be studied include the spectral cooling rates associated with carbon dioxide, particularly for the troposphere, and errors associated with the approximations for the treatment of the CFC's.

The plan at SUNY Albany is to complete the testing and documentation of the new longwave radiation parameterization for use in general circulation model. The effect on model climate simulations will be conducted by comparing with the earlier version.

Task 2:

The work at SUNY Albany will focus on testing and documentation of the new longwave radiation parameterization for use in general circulation model. The effect on model climate simulations will be conducted by comparing with the earlier version.

We plan to complete the study of the ozone depletion effect. "Real-time" (including the effects of ocean-delay) scenario runs are also planned for the 1979-1990 period and the results will be compared to the steady-state responses.

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