DOE/ER/61644--T1
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APR 24 1996

FINAL REPORT

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OBSERVATIONS AND SIMULATIONS OF CLIMATE FORCINGS AND FEEDBACKS

DOE Interagency Agreement No. DE-AI02-93ER61644

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February 1996

The research conducted under this Interagency Agreement sought to use available satellite data sets to document a variety of climate feedback processes by understanding the mechanisms of current climate variability (seasonal, interannual, temperature dependence). Comparisons with feedback processes operating in the GCM were performed to determine which aspects of the variability serve as the most reliable proxies for decadal climate change. We report on three general areas of progress: upper troposphere water vapor, low cloud optical thickness, and tropical cumulus anvil clouds.

Upper troposphere water vapor: We analyzed SST perturbation climate change simulations with the GISS GCM to understand the physical processes causing strong positive upper troposphere water vapor feedback (Del Genio et al., 1991). Our analysis of the GCM moisture budget revealed large increases in cumulus subsidence drying in the warmer climate, as predicted by Lindzen. However, this was more than compensated for by large increases in upward transport of water vapor by the large-scale dynamics, particularly by large-scale eddies. The feedback is not primarily associated with a stronger circulation, but rather with an increase in the vertical humidity gradient along which the transport occurs. The strengthening of the vertical humidity gradient in a warming climate is effectively guaranteed by the decrease in temperature with altitude in the troposphere combined with the extreme nonlinearity of the Clausius-Clapeyron equation, regardless of the changes in relative humidity that occur. The seasonal cycle of upper troposphere water vapor in midlatitudes, as documented by the SAGE II satellite data set (Rind et al., 1992), serves as a useful proxy for the climate feedback processes (Del Genio et al., 1994). SAGE II sees large seasonal increases in upper level specific humidity from winter to summer and slight increases in relative humidity. The GISS GCM reproduces these changes, and an analysis of the GCM moisture budget indicates that increased upward moisture transport in summer by large-scale eddies, despite the eddies themselves being weaker in summer, is responsible for the higher midlatitude moisture content then. This is identical to the process operating in the GCM climate change simulations.

Low cloud optical thickness and cover: Conventional wisdom holds that the liquid water content of clouds should increase with temperature, thus implying increased optical thickness as well and a negative cloud optics feedback in a climate change. We analyzed ISCCP data and showed that for low clouds, optical thickness increases with temperature only at cold temperatures and primarily over land; at high temperatures and over most ocean regions, optical thickness decreases with

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temperature instead (Tselioudis et al., 1992). The GISS GCM, which includes a new prognostic cloud water parameterization for stratiform clouds, reproduces this behavior (Del Genio et al., 1996). Analysis of the contributions to optical thickness variations in the GCM shows that systematic decreases in cloud physical thickness with warming can account for the observed optical thickness behavior. A unique feature of the parameterization, stability-dependent subgrid-scale vertical cloud thickness variations, is instrumental in this regard. Preliminary analysis of microwave water radiometer data, Belfort ceilometer cloud base data, and satellite cloud top height data at the ARM SGP CART site appear to verify the control of cloud optical thickness variations by physical thickness variations. The potential of the temperature-dependent optical thickness feedback to alter the magnitude of polar amplification of climate warming was pointed out by us (Tselioudis et al., 1993), and this has recently been verified in doubled carbon dioxide simulations with the GISS GCM with and without low cloud optical thickness feedbacks. We also used several multi-decadal GCM simulations to illustrate that positive feedbacks in subtropical low cloud amount can induce unforced natural variability of the climate of a magnitude similar to that observed over the past century, even in the absence of varying ocean dynamics (Miller and Del Genio, 1994).

Tropical cumulus anvil clouds: The thermostat hypothesis of Ramanathan and Collins asserts that as sea surface temperature rises in the tropics, thickening of cumulus anvil clouds will reduce surface solar absorption sufficiently to limit further warming, thus acting as an important negative feedback limiting climate sensitivity. The thermostat hypothesis was based on local changes in ERBE cloud forcing over the ENSO cycle. We used ISCCP data to demonstrate that these apparent negative feedbacks were simply due to shifts in the location of deep convection associated with general circulation changes over ENSO, and that averaged over the entire tropical Pacific basin, ENSO changes in shortwave radiation are negligible compared with changes in surface evaporation (Fu et al., 1992). Recent SST perturbation simulations with the GISS GCM indicate that global cloud feedback is quite sensitive to the processes that determine climate changes in tropical cumulus anvil clouds. If SST changes are spatially uniform, thus limiting changes in the general circulation, then anvils brighten considerably with warming and a negative cloud feedback results; but if the SST gradient weakens with warming, as is suggested by several coupled ocean-atmosphere models, then the Walker circulation weakens as well, causing only small changes in anvil cloud water content by comparison and a weakly positive cloud feedback (Del Genio et al., 1996).

In addition, during the period covered by this proposal, we participated in both the FANGIO and AMIP model intercomparison projects. The GISS GCM had one of the highest sensitivities in the original Cess et al. comparison (Cess et al., 1990; Randall et al., 1992), but the recent version with prognostic water has one of the lower sensitivities (Cess et al., 1996a). The GCM had modest positive snow feedback in a perpetual April simulation (Cess et al., 1991; Randall et al., 1994), and was one of the most accurate compared to line-by-line calculations in comparisons of carbon dioxide radiative forcing (Cess et al., 1993). The GISS GCM is also one of the most accurate in validations against ERBE seasonal cloud forcing differences (Cess et al., 1996b). Finally, AMIP intercomparisons indicate that the GISS GCM is among the best in validations of its cloud cover variations and interannual changes in the tropical general circulation.

Refereed publications resulting from support by the Quantitative Links Program include:

- Cess, R.D., et al., 1990: Intercomparison and interpretation of climate feedback processes in 19 atmospheric general circulation models. *J. Geophys. Res.*, **95**, 16601-16615.
- Cess, R.D., et al., 1991: Interpretation of snow-climate feedback as produced by 17 general circulation models. *Science*, **253**, 888-892.
- Cess, R.D., et al., 1993: Uncertainties in carbon dioxide radiative forcing in atmospheric general circulation models. *Science*, **262**, 1252-1255.
- Cess, R.D., et al., 1996a: Cloud feedback in atmospheric general circulation models: An update. Submitted to *J. Geophys. Res.*
- Cess, R.D., et al., 1996b: Comparison of atmospheric general circulation models to satellite observations of the seasonal change in cloud-radiative forcing. *J. Geophys. Res.* (in preparation).
- Del Genio, A.D., A.A. Lacis and R.A. Ruedy, 1991: Simulations of the effect of a warmer climate on atmospheric humidity. *Nature*, **351**, 382-385.
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thickness on climate warming. *Nature*, 366, 670-672.

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