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UCRL-86602
PREPRINT

CONF-810396--1

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OF MODEL FEEDBACKS**

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This paper was prepared for inclusion in the
proceedings of the La Jolla Institute
Workshop, "Responsible Interpretation of
Atmospheric Models and Related Data,"
Scripps Institution of Oceanography,
La Jolla, CA March 9-11, 1981

August 1981

Lawrence
Livermore
Laboratory

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DECOMPOSITION OF RADIATIONAL EFFECTS OF MODEL FEEDBACKS

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ABSTRACT

Three separate doubled CO_2 experiments with the LLNL SDM (statistical dynamic model) are used to illustrate our efforts to study the climate dynamics, feedbacks and interrelationships of meteorological parameters by decomposing and isolating their individual effects on radiation transport.

INTRODUCTION

A climate model run in the annual mean mode (constant mean annual solar insolation at each latitude) by eliminating diurnal and seasonal variations quickly approaches and remains close to a state of thermal and dynamic equilibrium. It thus provides a vehicle for relatively easily isolating the effects of individual parameters on the radiation balance and thereby estimating their effects on the planetary climate.

The method requires two parallel runs with the same model, a normal or control case and a perturbed case, each continued to equilibrium — i.e. until there are no longer progressive changes in temperatures, winds, clouds, precipitation, etc. For each of these equilibrium cases there is a model computed radiation balance in which the modeled planet is radiating energy to space at very nearly the same rate as it is receiving it from the sun. A major advantage of the annual mean mode is that this is true at each and every time step, not just when averaged over the annual cycle or over the diurnal cycle in a period near the equinoxes.

Using these two equilibrium data sets, one can individually and in any desired combination replace control case parameter fields with the corresponding field(s) from the perturbed case and recompute the resulting radiation balance in the hybrid representation of the earth and its atmosphere. All differences in radiation flux (hybrid minus control), whether examined at the planetary surface, the tropopause, or the top of the atmosphere, can unequivocally be attributed to the differences (perturbed minus control) in the perturbed field(s). (We are attempting to find a way to approximate this very powerful technique with a diurnally and seasonally varying model.)

To illustrate the technique and its power, we have selected three preliminary doubled CO_2 experiments recently performed with the LLNL SDM climate model.¹ The three experimental cases are as follows:

Case 1. Annual average with realistic topography.

Case 2. Annual average with idealized topography-30% land at each latitude except the poles and with no mountains.

Case 3. Same as 2 except ice-albedo feedback was forced by removing sea ice in the bands at 75 to 85°N and S. (Case 3 was run because, although there was no change in the area of sea ice in Case 2, it had started to melt and we wanted to see the effect of ice-albedo feedback. This case used the same control as Case 2, i.e. we assumed that doubling CO₂ removed all sea ice from the latitude bands at 75 to 85°N and S.).

Case 1 has been reported previously.^{2,3,4} Cases 2 and 3 have not been reported previously.

For these three cases the global mean differences in net, solar and IR radiative fluxes (perturbed minus control) in watts per meter squared [W/m²] are summarized in Tables 1, 2, and 3. The flux differences have been evaluated for the changes in each of the parameters: CO₂, H₂O, clouds, surface albedo (α_s) and temperature. Each of these parameters represents a complete planetary field with their changes (i.e., the perturbations) having been forced by the doubling of CO₂ (and the removal of the sea ice at 75 to 85°N and S in Case 3), but the changes in radiative flux due to each parameter were isolated by recomputing the radiation balance as each field in the control data set was replaced (only one at a time) by the corresponding field from the perturbed data set. Remember, however, that the warmer temperature also means warmer clouds, H₂O, CO₂, etc. The radiative fluxes are also broken down vertically to show the changes in radiative flux (or flux convergence) to the planet (i.e., at top of the atmosphere), the planetary surface, the stratosphere and the troposphere. Global mean changes in each parameter (induced by 2x CO₂) are given in the table headings in both absolute units and percentages. The change in temperature is a mass weighted average (not computed in Case 1) and no percentage change is given. The last two columns on the right of each table give the algebraic sum of the isolated radiative changes for the five parameters listed and the corresponding total flux differences between the equilibrium runs (perturbed minus control), i.e. including synergisms and any residual small imbalances in the two "equilibrium" radiation balances. Also given in the small square at the upper right of each table is the mean global (and hemispheric) change in surface air temperature.

RESULTS

An examination of the tables reveals the following general results.

Instantaneous doubling of CO₂ (2x CO₂) increases the radiative heat loss of the stratosphere by 1.5-2.0 W/m² but causes a net radiative gain to the planet of 2.5-3.0 W/m². The increased radiative flux to the surface is about half the planetary gain, and that to the troposphere is equal to or even larger than the net gain to the planet, causing a net gain to the troposphere/surface system of 4 to 5 W/m². Thus the immediate effect

Table 1. Changes in net received radiative flux for doubled CO₂ — perturbed minus control.

Case 1: Annual average mode with realistic distribution of land and mountains.

Sfc temp change:	
Global	1.42K
N.H.	2.33K
S.H.	0.51K

Net flux to: [W/m ²]		2xCO ₂	ΔH ₂ O	ΔClouds	Δα _s	ΔT	Sum of isolated components	Total ΔF including synergisms
		320ppm +100%	0.22gm/cm ² 10.08%	0.011 1.96%	-0.004 -2.26%			
Planet	Net	2.55	2.08	-1.34	0.39	-3.53	0.16	0.47
	S	—	0.34	-0.57	0.39	—	0.17	0.04
	IR	2.55	1.74	-0.76	—	-3.53	-0.01	0.43
Strato- sphere	Net	-1.64	-0.24	<0.01	-<0.01	1.53	-0.35	-0.01
	S	—	-<0.01	<0.01	-<0.01	—	-<0.01	0.00
	IR	-1.64	-0.23	0.00	—	1.53	-0.34	-0.01
Tropo- sphere	Net	2.40	0.68	-3.95	-0.12	-3.12	-4.11	-3.36
	S	—	0.80	1.04	-0.12	—	1.71	1.52
	IR	2.40	-0.12	-4.98	—	-3.12	-5.90	-4.89
Surface	Net	1.78	1.64	2.60	0.52	-1.94	4.62	3.84
	S	—	-0.45	-1.61	0.52	—	-1.54	-1.49
	IR	1.78	2.09	4.22	—	-1.94	6.16	5.33

Table 2. Changes in net received radiative flux for doubled CO₂ — perturbed minus control.

Case 2: Annual average mode with idealized topography (ice in)

Sfc temp change:	
Global	0.78K
N.H.	0.78K
S.H.	0.78K

Net flux to: [W/m ²]		2xCO ₂	ΔH ₂ O	ΔClouds	Δα _s	ΔT	Sum of isolated components	Total ΔF including synergisms
		320ppm	0.24gm/cm ²	0.008	0.0	1.08		
		+100%	8.36%	1.27%	0.0			
Planet	Net	2.94	1.48	-0.84	--	-3.80	-0.22	-0.34
	S	--	0.27	-0.89	--	--	-0.62	-1.14
	IR	2.94	1.21	0.05	--	-3.80	0.40	0.80
Strato- sphere	Net	-1.88	-0.04	0.01	--	1.64	-0.27	-0.01
	S	--	-0.004	-0.01	--	--	0.01	0.02
	IR	-1.88	-0.036	<0.01	--	1.64	-0.28	-0.03
Tropo- sphere	Net	3.55	0.91	-0.49	--	-6.30	-2.32	-3.00
	S	--	0.71	0.31	--	--	1.03	1.32
	IR	3.55	0.20	-0.80	--	-6.30	-3.35	-4.32
Surface	Net	1.28	0.60	-0.37	--	0.86	2.37	2.66
	S	--	-0.44	-1.32	--	--	-1.65	-2.48
	IR	1.28	1.04	0.85	--	0.86	4.03	5.14

Table 3. Changes in net received radiative flux for doubled CO₂ — perturbed minus control.

Case 3: Annual average mode with idealized topography (ice out)

Sfc temp change:	
Global	1.50K
N.H.	1.50K
S.H.	1.50K

Net flux to: [W/m ²]		2xCO ₂	ΔH ₂ O	ΔClouds	Δα _s	ΔT	Sum of isolated components	Total ΔF including synergisms
		320ppm	0.34gm/cm ²	0.003	-0.018	1.72K		
		+100%	11.76%	0.50%	-13.92%			
Planet	Net	2.94	3.10	-0.58	1.09	-6.42	0.14	0.48
	S	—	0.41	-0.33	1.09	—	1.17	1.11
	IR	2.94	2.69	-0.25	—	-6.42	1.03	-0.63
Strato- sphere	Net	-1.88	-0.06	0.01	-0.02	1.70	-0.24	-0.01
	S	—	-0.01	<0.01	-0.02	—	-0.02	-0.02
	IR	-1.88	-0.05	<0.01	—	1.70	-0.22	0.01
Tropo- sphere	Net	3.55	2.26	-0.40	-0.22	-7.97	-2.78	-2.64
	S	—	1.03	0.23	-0.22	—	1.04	1.01
	IR	3.55	1.23	-0.63	—	-7.97	-3.82	-3.65
Surface	Net	1.27	0.90	-0.19	1.33	-0.15	3.16	3.13
	S	—	-0.61	-0.57	1.33	—	0.15	0.12
	IR	1.27	1.51	0.38	—	-0.15	3.01	3.01

of doubling CO_2 will be a cooling of the stratosphere but an overall warming of the total atmosphere that will be concentrated in the troposphere. This redistribution of radiative energy within the atmosphere and the net gain to the planet guarantee that feedback processes will be activated. The most fundamental response is an overall warming of the atmosphere, computed to be 1-2K at equilibrium. Instantaneous insertion of the new equilibrium temperatures (ΔT) produces the changes in net radiative flux given in Column 5 of the tables. (Remember that the temperature of the clouds, H_2O , CO_2 and lower boundary are all changed to the perturbed temperature values.) Except at the surface, these directly oppose and generally exceed the immediate effects of $2\times\text{CO}_2$. At the surface; Case 1 still more than cancels the effect of $2\times\text{CO}_2$ but Case 2 increases the surface warming and Case 3 has almost no effect. This seems to indicate that the temperature induced radiation loss at the surface in Case 1 is due more to the change in clouds than to doubling CO_2 .

The next most significant response is the ~10% increase in precipitable water ($\Delta\text{H}_2\text{O}$) due to the 1-2K warming of the atmosphere. The equilibrium distribution of water vapor, when inserted alone, produces the changes in radiative flux given in Column 2 of the tables. These tend to parallel the immediate effects of $2\times\text{CO}_2$ except that the cooling of the stratosphere is very small and a larger fraction of the increased radiative flux goes to the surface. This is a positive feedback (or additional greenhouse effect) induced by the doubling of CO_2 , and requires (in the absence of other effects) an additional increase in atmospheric temperature to increase the back radiation to space. In contrast to the effects of $2\times\text{CO}_2^*$ and ΔT , $\Delta\text{H}_2\text{O}$ leads to increased solar absorption in the troposphere, which leaves less to be absorbed at the surface.

In each of these experiments, total cloud cover increased by 0.5 to 2% (Δcloud) and caused an overall increase in the net radiative flux of the planet to space (cooling). In the troposphere there was a tendency for increased IR emission to balance increased solar absorption and at the surface a tendency for increased IR absorption to cancel the decrease in solar absorption. Beyond this, the numbers indicate considerable differences among the three experiments that we plan to investigate further.

In Case 1, the surface albedo decreased ($\Delta\alpha_s$), mainly due to wetter, darker soil leading to an increase in solar absorption at the surface of 0.5 W/m^2 . The increased solar absorption by the planet was slightly smaller than this because there was less reflected sunlight to be absorbed in the troposphere — causing a decrease there. In Case 2, α_s remained unchanged. In Case 2 with doubled CO_2 , the ice at 80°N was melting but it was so thick we didn't wait for it to melt completely. We removed the ice at 80°N and S and reran the experiment as Case 3. Since there was no tendency for ice to reform at these latitudes this appeared to be a valid test of the effect of ice-albedo feedback, however, in so far as Case 3 represents a valid experiment (i.e. achieved a valid equilibrium state of the model) it appears to render Case 2 invalid. Both are included here merely to

*We do not now include the effects of CO_2 on solar radiation.

illustrate the analysis technique. Case 3 had a 6-fold larger decrease in α_s than in Case 1, but since it was all in high latitudes the effect on solar absorption was only a little over twice as large as in Case 1. As would be expected, the changes in both α_s and clouds had essentially no effect on the stratosphere.

Column 6 of Tables 1, 2, and 3 shows the sum of the isolated radiative effects due directly to the changes in CO_2 , H_2O , clouds, α_s and T while Column 7 gives corresponding differences in flux between the equilibrium perturbed and control runs. Fortuitously, the five isolated contributions to changes in planetary radiative flux balance better than the difference between the two "equilibrium" runs—indicating that in at least one of the latter the planetary energy balance was not quite in equilibrium at the time step selected. Note, however, that the stratospheres appear to have been close to equilibrium.

Looking at the overall changes in radiative flux due to doubling CO_2 , we see that the 2.5-3 W/m^2 reduction in planetary IR radiation to space from $2\times\text{CO}_2$ alone is augmented by positive feedback from the ~10% increase in water vapor and any decrease in α_s , whether due to a wetter, darker soil and/or to melting of sea ice. That portion of this decreased rejection of energy to space not compensated by increased clouds leads to an atmospheric warming increasing back radiation until the outgoing radiation deficit is made up. Beyond this there is a vertical redistribution of radiative flux convergence. The 1.25-1.75 W/m^2 increase in IR flux received at the surface due to the instantaneous doubling of CO_2 results, at equilibrium, in an increased flux to the surface of 2.5-4.5 W/m^2 , most of which comes from or is lost by the troposphere. To achieve stability, this shift in radiative flux convergence must be compensated by an equivalent transfer of energy from the surface to the troposphere. Model results indicate that this transfer is accomplished mainly by increased convection, i.e. surface evaporation followed by precipitation and rerelease of the latent heat in the troposphere.

Finally, note that doubling CO_2 caused a surface warming of 1.42K in Case 1, 0.78K in Case 2 and 1.50K in Case 3. These may appear small compared to other model results, but note that with realistic land distribution the surface temperature warms 2.33K in the Northern Hemisphere — which is the domain for which most models have been calibrated. Subsequent to the running of Case 1 there were several model changes including a change in the IR radiation routine. However, the idealized topography (i.e., 30% land at each latitude and no mountains) is believed to account for more of the differences between these $2\times\text{CO}_2$ experiments than the model changes.

EPILOGUE

In the attribution of any climate change to CO_2 , it has been suggested⁵ that there will be a spectral redistribution of IR radiation from the planet to space, i.e. decreased radiation in the CO_2 14 μ band made up by an increase in the 8-12 μ atmospheric window. To increase

radiation in the window region requires a black body radiator which is heated to a higher temperature or increased in area, i.e. a higher surface temperature or more and/or warmer clouds. In Cases 2 and 3 we see very little contribution to additional IR radiation to space coming from the surface or from changes in clouds. Most of the needed increase in IR radiation to space comes from the troposphere and is therefore due to the higher temperatures at which CO_2 , H_2O and clouds radiate at the perturbed as opposed to the control temperature. This suggests that doubling of CO_2 may not necessarily lead to much spectral redistribution of the planetary outgoing IR radiation. While Case 1 gives the most support for such a redistribution, we see that even there the potential black body radiators (clouds and planetary surface) provide at most 2.28 of the 5.04 W/m^2 required to balance the planetary greenhouse effect of $2 \times \text{CO}_2$ and the induced positive feedbacks from $\Delta\text{H}_2\text{O}$ and ΔO_3 . In Cases 2 and 3 these black body radiators provide almost no compensation for the greenhouse effect -- essentially all of the compensation is coming from the warmer perturbed troposphere, i.e. from the warmer tropospheric CO_2 , H_2O and clouds. (As this statement implies, our analysis does not yet isolate such individual effects as raising the clouds alone to the perturbation temperature.) However, this suggests the types of questions we can begin to address with this and other analysis techniques.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

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