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Abstract

The rapidly rising CO_2 level in the atmosphere has led to proposals of climate stabilization via "Geoengineering" schemes that would mitigate climate change by intentionally reducing the solar radiation incident on earth's surface. In this paper, we address the impact of these climate stabilization schemes on the global hydrological cycle, using equilibrium simulations from an atmospheric general circulation model coupled to a slab ocean model. We show that insolation reductions sufficient to offset global-scale temperature increases lead to a decrease in the intensity of the global hydrologic cycle. This occurs because solar forcing is more effective in driving changes in global mean evaporation than is CO_2 forcing of a similar magnitude. In the model used here, the hydrologic sensitivity, defined as the percentage change in global mean precipitation per degree warming, is 2.4% for solar forcing, but only 1.5% for CO_2 forcing. Although other models and the climate system itself may differ quantitatively from this result, the conclusion can be understood based on simple considerations of the surface energy budget and thus is likely to be robust. Compared to changing temperature by altering greenhouse gas concentrations, changing temperature by varying insolation results in larger changes in net radiative fluxes at the surface; these are compensated by larger changes in latent and sensible heat fluxes. Hence the hydrological cycle is more sensitive to temperature adjustment *via* changes in insolation than changes in greenhouse gases. This implies that an alteration in solar forcing might offset temperature changes or hydrological changes from greenhouse warming, but could not cancel both at once.

Introduction

The rapid rise in the rate of fossil fuel emission in the recent years has revived the discussion of mitigating climate change via "geoengineering" schemes (1-4). The proposed schemes fall into two categories. The first involves reducing the solar radiation absorbed by the climate system by an amount that balances the reduction in outgoing terrestrial radiation due to the increase in the atmospheric CO_2 and other greenhouse gases (1, 5-12). The other class of schemes typically removes the atmospheric CO_2 and sequesters it into the terrestrial vegetation, ocean, or into deep geologic formations.

Climate modeling studies have investigated the viability of the first category of schemes. The first equilibrium simulation studies on this subject (13, 14) show that the schemes that reduce incoming solar radiation ("insolation") would largely mitigate even regional and seasonal climate change from a doubling and quadrupling of CO_2 even though the spatial and temporal pattern of radiative forcing from greenhouse gases differs markedly from that of sunlight. These modeling studies find that residual temperature changes in a climate with increased greenhouse gases and appropriately reduced insolation are much smaller than the changes due to CO_2 increases alone.

Further modeling work investigating the impact of climate stabilization schemes on the terrestrial biosphere (15) indicates that climate stabilization would tend to limit changes in vegetation distribution brought on by climate change, but would not prevent CO_2-induced changes in Net Primary Productivity (NPP) or biomass. However, concerns have been raised that CO_2 effects on ocean chemistry could have deleterious consequences for marine biota due to ocean acidification which is not mitigated by the geoengineering schemes (16).

Investigations of transient climate response to geoengineering using an intermediate-complexity global climate model that includes an interactive carbon cycle

(17) suggest that the climate system responds quickly to artificially reduced solar radiation; hence, there may be little cost to delaying the deployment of geoengineering strategies until such time as "dangerous" climate change is imminent. These studies also find that a failure of the geoengineering scheme could lead to very rapid climate change, with warming rates up to twenty times greater than present-day rates.

A limitation of the previous modeling studies is that they do not evaluate the impact of these geoengineering schemes on the global hydrological cycle. A recent observational study (18) shows that there was a substantial decrease in precipitation over land and a record decrease in runoff and discharge into the ocean following the eruption of Mount Pinatubo in 1991. It cautions that a weakened hydrological cycle, including droughts, could arise from geoengineering solutions.

Modeling studies do indicate a decline in precipitation in the geoengineered climate (13, 15, 17). However, this decline in precipitation has gone largely unnoticed and was not investigated in detail. It is not generally understood why there should be a reduction in the intensity of the global hydrological cycle in the geoengineered climate while there is mitigation in terms of surface temperature change. The dependence of global mean precipitation on the forcing mechanism (19) offers some insight into this problem. This paper investigates the sensitivity of the global mean precipitation to CO_2 and solar forcings separately and explains the causes for the weakening of the global hydrological cycle in a geoengineered world. We analyze existing equilibrium simulations (15). We emphasize that equilibrium simulations can only qualitatively predict the transient responses of the climate system. Quantitative results from the model used here will differ from results of other models and from the real climate system; nonetheless, we believe that the basic phenomenon described here — a greater hydrological sensitivity to solar *vs*. greenhouse forcing — is fundamental and can be understood through a straight-forward analysis of the global energy budget.

Model

The simulations presented here use version 3 of the atmospheric general circulation model, Community Climate Model (CCM3) developed at the National Center for Atmospheric Research (20) which has been coupled to a terrestrial biosphere model, Integrated Biosphere Simulator or IBIS (21, 22). The horizontal resolution is approximately 2.8° in latitude and 2.8° in longitude. The atmosphere model has 18 levels in the vertical. We use a version of CCM3 that is coupled to simple slab ocean-thermodynamic sea ice model, which allows for a simple interactive surface for the ocean and sea ice components of the climate system. The slab ocean model employs a spatially and temporally varying prescribed ocean heat transport and spatially varying mixed layer-depth, which ensures replication of realistic sea surface temperatures and ice distributions for the present climate.

Experiments

To assess the impacts of increased atmospheric CO_2 content on the global hydrology, we performed four model simulations (15): (i) "Control", with a CO_2 content of 355 ppm and incoming solar flux of 1367 W m^{-2}; (ii) "2xCO_2", with doubled atmospheric CO_2 content (710 ppm), and the same incoming solar flux as the Control simulation; (iii) "Solar" with a CO_2 content that is the same as Control, but solar flux reduced by 1.8%; and (iv) "Stabilized", with doubled atmospheric CO_2 content and the solar flux reduced by 1.8%. This reduction in solar luminosity was chosen to approximately offset the surface temperature impacts from a CO_2 doubling in this model. Geoengineering schemes would effect this reduction in solar radiation through, for example, the placement of reflecting or scattering devices between the Earth and Sun (2, 8, 10-12). For all experiments, the model was initialized with a state corresponding to present day conditions. From this initial state, the model typically needs to run for at least ~75 simulated years to approach quasi-equilibrium. The climate statistics presented below are the averaged values over the last 25 years of model simulations. During this period, the global average net flux of energy at the top of the atmosphere is, in absolute terms, less than 0.1 Wm^{-2}, indicating that the system is very nearly in equilibrium (Table 1). In all the experiments, the drifts in global mean surface temperature during the 25 year period analyzed are of order 10^{-4} K , and the interannual variability as measured by the standard deviation of the global mean surface temperature is ~ 0.06 K. These are both very small compared to differences among the different simulations.

Results

Compared to the Control case, the global- and annual-mean near-surface temperature increases by 2.42 K in the 2xCO_2 experiment and decreases by nearly identical amount in the Solar experiment (Table 1). By design, the surface temperature of the Stabilized case is very similar to Control (13-15).

Temperature changes in the 2xCO_2 and Solar are significant at the 1% level over all regions of the globe (Fig. 1). The changes are larger over land and high latitude regions, in agreement with published literature (23). The residual temperature changes in the Stabilized case are significant over ocean and northern land areas but are much smaller when compared to the 2xCO_2 or Solar cases. The vertical distribution of global mean temperature shows a decrease (increase) in lapse rate in the troposphere in the 2xCO_2 (Solar) case (Fig. 2). The mean stratospheric cooling exceeds 6 K in the 2xCO_2 case and it is less 1 K in the Solar case. As noted in previous studies (13, 14), the stratospheric cooling is not mitigated (Fig. 2)

The total water vapor content of the atmosphere is enhanced by 15.2% in the 2xCO_2 experiment and reduced by the same amount in the Solar case (Table 1). The changes in water water-vapor content reflect the response of specific humidity to temperature change when the relative humidity does not change under climate change (19, 24). The specific humidity response reflects an increase of total water vapor content consistent with the Clausius-Clapeyron relationship; ~6.5% change per every degree of temperature change. There is clear mitigation of climate change in terms of surface temperature and vapor content of the atmosphere in the Stabilized case.

The mitigation is less exact, however, in the case of global mean precipitation: precipitation increases by 3.7% for the 2xCO_2 case but decreases by 5.8% in the Solar experiment (Table 1). Precipitation in the Stabilized case is 1.7% less than in Control. Since global mean precipitation equals global mean evaporation, similar changes are also seen in latent heat fluxes. This residual change in precipitation implies that the hydrologic sensitivity of the climate system depends on the forcing mechanisms. We define the hydrologic sensitivity as the percentage change in precipitation per degree of temperature change. The hydrologic sensitivities in the model used here are 1.53% for the 2xCO_2 case and 2.42% for the Solar case. The larger hydrologic sensitivity to solar forcing leads to a net decline in global precipitation in the Stabilized case relative to the Control.

Since precipitation changes are driven by evaporation, our discussion will focus on the changes in latent heat fluxes (Fig. 1 and 2). The changes in this flux in the 2xCO_2 case show increases in all regions, with larger enhancements in the Northern Hemisphere high latitude land regions (Fig. 1). Latent heat fluxes decrease in the Solar case and the reduction is stronger in the tropics. The evaporation changes are significant at the 1% level over 61% and 83% of the globe in the 2xCO_2 and Solar experiments, respectively. A general decline in latent heat fluxes can be clearly seen in the Stabilized case with the reductions in the tropics being stronger and statistically significant at the 1% level. These residual changes are significant at the 1% level over 42% of the globe. Most of the non-compensation that is statistically significant is confined to the tropics.

Why are the hydrologic sensitivities different for greenhouse vs. solar forcing? The vertical distribution of radiative forcing for 2xCO_2 and Solar (25) provides a simple explanation. Radiative forcing by CO_2 mainly heats the troposphere, while solar forcing mainly heats the surface (25). Therefore, the energy available for latent and sensible heat fluxes (at the surface) is more strongly affected by solar forcing than by greenhouse forcing that has the same magnitude at the tropopause.

A more complete explanation requires quantitative consideration of vertical fluxes of energy at the surface. The time-mean, globally averaged surfaced energy flux differences between any two equilibrium states must sum to zero:

$$\Delta R + \Delta S - \Delta L - \Delta H = 0 \qquad (1)$$

where ΔR, ΔS, ΔL, and ΔH represent the differences in longwave radiation, shortwave radiation, latent heat and sensible heat, respectively. The sign convention is that downward fluxes are positive for radiation and negative for latent and sensible heat. It is useful to resolve the radiative fluxes into "forcing" and "response" components, where the "forcing" is usually defined to be the instantaneous impact of some perturbation on radiation (but more generally accounts for any radiative response unrelated to climate change). Then equation (1) becomes

$$F + \Delta R_r + \Delta S_r - \Delta L - \Delta H = 0 \qquad (2)$$

where F is the sum of shortwave and longwave radiative forcing and the subscripts r indicate that the terms represent only the "response" component of the change in radiation.

In our model the surface forcing in the Solar case is about -3 Wm^{-2} but in the CO_2 case is only a few tenths of a Wm^{-2}. In the Stabilized case, the forcing is the sum of these individual forcings (~-2.5 Wm^{-2}) and is therefore responsible for all but a few tenths of a Wm^{-2} of the changes in net radiative surface flux plotted in fig. 3. This means that the radiative "response" terms in equation 2 can be neglected and the surface radiative forcing must be balanced by changes in latent and sensible heat:

$$\Delta L + \Delta H \approx F \qquad (3)$$

It should not be surprising that the radiative "response" is approximately zero in this Stabilized case, since the variables affecting radiative transfer (temperature, water vapor, clouds) do not change much relative to the Control case (see fig. 2, for the vertical temperature structure).

A similar analysis of the atmospheric energy budget leads to a complementary result: changes in the heating rate of the atmosphere due to radiative forcing must be balanced by changes in sensible plus latent heat release if the global mean temperature remains unchanged. In the Stabilized case, the difference between the radiative forcing at the top of the atmosphere and the surface (the radiative forcing of the atmosphere) is balanced by the change in the sum of latent and sensible heat fluxes. Because in this case the net radiative forcing at the top of the atmosphere is, by design, about zero, equation 3, now applied to the atmosphere, yields the same change in sensible plus latent heat that was found at the surface.

Equation 3 does not constrain the partitioning between the latent and sensible heat fluxes that together must balance the radiative forcing. In the control climate the ratio of the sensible to latent heat flux (i.e., the Bowen ratio) is roughly 0.2 so it seems likely that under perturbed conditions the latent heat flux response will dominate (as it does in the model used here). This is true not only of the Stabilized case, but also in the individual forcing runs (2xCO_2 and Solar) where, in fact, the sensible and latent heat flux changes are of opposite sign (see fig. 3). The dominance of latent heat flux changes relative to sensible heat flux changes means that in climates with global mean temperature close to the control, changes in precipitation can be predicted from knowledge of the surface radiative forcing alone.

Discussion

While climate (i.e. temperature) sensitivity is in general roughly the same for different forcing mechanisms, hydrologic sensitivity can be different. In the model used here, the temperature response to a reduction in insolation is of nearly equal magnitude to the response to an increase in CO_2 having the same nominal radiative forcing. However, the hydrologic sensitivity to increasing atmospheric CO_2 is 1.5% per Kelvin, whereas for a reduction in solar radiation, the hydrologic sensitivity increases to 2.4% per Kelvin. Thus, shortwave forcing, which primarily impacts the surface, is more effective in driving changes in global evaporation/precipitation than is CO_2 forcing of a similar magnitude, which mostly impacts the atmosphere. The reason for this, in essence, is that if climate is warmed by an increase in insolation, the surface sees an increase in incident shortwave plus an increase in downwelling longwave from the warmer atmosphere above. By contrast, if the climate is warmed by increasing greenhouse gases, the surface sees only the increased longwave flux. The differential surface radiation drives changes in evaporation that require equal changes in precipitation.

Whether results found in the model used here carry over to other models and to the climate system itself depends on whether equation 3 applies universally. The simplification leading to equation 3 is that in comparison to the radiative forcing and the combination of latent plus sensible heat changes, the response of surface radiative fluxes to surface radiative forcing in the absence of global mean temperature change is weak in the Stabilized case.

Many studies (25-28) have shown that for any given model, the radiative response of the climate system, as monitored by changes in top of the atmosphere net radiation averaged annually and globally, is linearly related to the global mean surface temperature change. This, in fact, is a consequence of the empirical result that for any given model the equilibrium climate sensitivity, defined as the ratio of global mean temperature change to the global mean forcing, is roughly independent of the characteristics of the forcing (e.g., spatial or temporal pattern). In the model used here this empirical relationship appears to extend to radiative responses at the surface too. If other models were forced as in the Stabilized case, with essentially no change in surface temperature, the net radiative response at the top of the atmosphere would be expected to be approximately zero. It is difficult to see how any model under these conditions could respond with large changes in surface radiative response if there is little change in tropospheric or surface temperatures. Therefore, it is likely that the rough balance between surface radiative forcing and the combined changes of latent and sensible heat flux is not a peculiar result of the model used here. Furthermore, if the latent heat changes dominate (relative to sensible heat changes) then the conclusion that precipitation decreases in the Stabilized case is robust.

Our results are consistent with earlier modeling experiments which showed a decrease in precipitation for an increase in atmospheric CO_2 when sea surface temperatures (SST) were fixed (29, 30). This situation is similar to our Stabilized case in that greenhouse gases increase without an associated change in the surface temperature. In these experiments, as in our experiment, the enhanced heating of the atmosphere due to the CO_2 forcing leads to a reduction in latent heat release (reduced precipitation), since the radiative response of the system must be small due to the fixed SST constraint. At the surface, in these experiments, the reduced cooling by evaporation implies enhanced sequestration of heat by the oceans.

Because the model used here lacks a sophisticated dynamic ocean and sea ice model, the transient effects of climate change and its impact on global hydrology are not assessed in this study. The model used here also lacks the feedbacks associated with an interactive carbon cycle and other biogeochemical processes. Other atmospheric GCMs coupled to a full, three dimensional ocean and fully interactive carbon models and subjected to transient forcing would likely yield quantitatively different results. Nonetheless, we believe that the basic qualitative result that the hydrologic sensitivity is larger for solar forcing than CO_2 forcing is model-independent, and is a property of the real climate system.

The differing hydrologic sensitivities for greenhouse versus solar forcings have clear implications for the proposed geoengineering schemes that attempt to reduce the incoming solar radiation by injecting sulfate aerosols into the stratosphere or by placing mirrors or reflectors in space. While these schemes could possibly mitigate to a degree the harmful effects of rising surface temperature, they will lead to a less intense hydrologic cycle. Our investigation has centered only on the global hydrology; we have not analyzed regional details of hydrological changes due to geoengineering. Hydrological responses at the regional scale in the model used are relatively uncertain because of the model's weak hydrologic sensitivity; we find that the precipitation changes are significant at the 1% level over only 40% of the globe for a doubling of CO_2.

Besides a less-intense hydrologic cycle in the geoengineered world, as pointed out in our study, there are many reasons not to engage in geoengineering schemes for climate stabilization. Geoengineering of this kind will not mitigate the harmful effects of ocean acidification since the geoengineered world would still have higher concentration of atmospheric CO_2. Some stabilization schemes could adversely impact the ozone layer. CO_2-induced climate change would last multiple centuries since the atmospheric residence time scale of CO_2 is a few centuries; if geoengineering schemes are implemented, the commitments would have to be maintained over many centuries (16). It would be difficult to develop an international consensus to engage in a long-term large-scale geoengineering project (31), and technical failure of a stabilization scheme could be catastrophic (17).

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References

1. Angel, R. (2006) *Proceedings of the National Academy of Sciences of the United States of America* **103,** 17184-17189.
2. Crutzen, P. J. (2006) *Climatic Change* **77,** 211-219.
3. Gail, W. B. (2007) *Ieee Spectrum* **44,** 20-25.
4. Wigley, T. M. L. (2006) *Science* **314,** 452-454.
5. PSAC (1965) in *President's Scientific Advisory Committee, Restoring the quality of our environment, Appendix Y4, Atmospheric Carbon Dioxide, Report by the US President's Scientific Advisory Committee* (The White House, Washington DC), pp. 111-133.
6. Budyko, M. I. (1977) *Climatic changes* (American Geophysical Union, Washington).
7. Seifritz, W. (1989) *Nature* **340,** 603-603.
8. NAS (1992) in *Policy implications of greenhouse warming: Mitigation, Adaptation and the Science Base* (National Academy Press, Washington D. C), pp. 433-464.
9. Watson, R. T., Zinyowera, M. C., Moses, R. H. & Dokken, D. J. (1995) in *Climate Change 1995* (Intergovernmental Panel on Climate Change, United Nations Environmental Program/World Meteorological Organization, Cambridge University Press, New York), pp. 799-822.
10. Flannary, B. P., Kheshgi, H., Marland, G. & MacCraken, M. C. (1997) in *Engineering response to Global Climate Change* (Lewis Publishers, University City, MO), pp. 403-421.
11. Teller, E., Wood, L. & Hyde, R. (1997) in *UCRL-231636 / UCRL JC 128715* (Lawrence Livermore National Laboratory, Livermore, CA).
12. Early, J. T. (1989) *J. Brit. Interplanet. Soc* **42,** 567-569.
13. Govindasamy, B. & Caldeira, K. (2000) *Geophysical Research Letters* **27,** 2141-2144.
14. Govindasamy, B., Caldeira, K. & Duffy, P. B. (2003) *Global and Planetary Change* **37,** 157-168.
15. Govindasamy, B., Thompson, S., Duffy, P. B., Caldeira, K. & Delire, C. (2002) *Geophysical Research Letters* **29,** 2061, doi: 10.1029/2002GL015911.
16. Bengtsson, L. (2006) *Climatic Change* **77,** 229-234.
17. Matthews, H. D. & Caldeira, K. (2007) *Proceedings of the National Academy of Sciences of the United States of America* **104,** 9949-9954.
18. Trenberth, K. E. & Dai, A. (2007) *Geophysical Research Letters* **34,** L15702, doi:10.1029/2007GL030524.
19. Allen, M. R. & Ingram, W. J. (2002) *Nature* **419,** 224-232.
20. Kiehl, J. T., Hack, J. J., Bonan, G. B., Boville, B. A., Williamson, D. L. & Rasch, P. J. (1998) *Journal of Climate* **11,** 1131-1149.
21. Foley, J. A., Prentice, I. C., Ramankutty, N., Levis, S., Pollard, D., Sitch, S. & Haxeltine, A. (1996) *Global Biogeochemical Cycles* **10,** 603-628.

22. Kucharik, C. J., Foley, J. A., Delire, C., Fisher, V. A., Coe, M. T., Lenters, J. D., Young-Molling, C., Ramankutty, N., Norman, J. M. & Gower, S. T. (2000) *Global Biogeochemical Cycles* **14,** 795-825.
23. Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., S.C.B. Raper, S. C. B., Watterson, I. G., A. J. Weaver, A. J. & Zhao, Z.-C. (2007) in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA).
24. Ross, R. J., Elliott, W. P., Seidel, D. J. & Participating AMIP-II Modeling Grp. (2002) *Journal of Hydrometeorology* **3,** 26-38.
25. Hansen, J., Sato, M. & Ruedy, R. (1997) *Journal of Geophysical Research-Atmospheres* **102,** 6831-6864.
26. Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, M., Bauer, S., Bell, N., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Del Genio, A., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Kelley, M., Kiang, N., Koch, D., Lean, J., Lerner, J., Lo, K., Menon, S., Miller, R., Minnis, P., Novakov, T., Oinas, V., Perlwitz, J., Perlwitz, J., Rind, D., Romanou, A., Shindell, D., Stone, P., Sun, S., Tausnev, N., Thresher, D., Wielicki, B., Wong, T., Yao, M. & Zhang, S. (2005) *Journal of Geophysical Research-Atmospheres* **110,** D18104, doi:10.1029/2005JD005776.
27. Ramaswamy, V. & Chen, C. T. (1997) *Geophysical Research Letters* **24,** 567-570.
28. Cox, S. J., Wang, W. C. & Schwartz, S. E. (1995) *Geophysical Research Letters* **22,** 2509-2512.
29. Mitchell, J. F. B. (1983) *Quarterly Journal of the Royal Meteorological Society* **109,** 113-152.
30. Yang, F. L., Kumar, A., Schlesinger, M. E. & Wang, W. Q. (2003) *Journal of Climate* **16,** 2419-2423.
31. Schneider, S. H. (2001) *Nature* **409,** 417- 421.

Figure captions

Figure 1 Changes in annual-mean surface temperature (top panels) and surface latent heat fluxes (bottom panel) in the 2xCO_2, Solar, and Stabilized cases relative to the Control. Hatching indicates the regions where the changes are significant at the 1% level. Significance level was estimating using a Student t-test. Temperature changes are large and significant everywhere in the 2xCO_2 and Solar cases. Though significant over large regions, temperature changes are small in the Stabilized case. Surface latent heat flux changes are significant over 61 and 83% over the globe in the 2xCO_2 and Solar cases. There is a general decrease over most of the regions in the Stabilized case relative to the Control, suggesting that geoengineering may lead to a weakened hydrologic cycle.

Figure 2 Changes in the vertical profile of the global- and annual-mean temperature (top panel), and in the meridional distribution of zonal mean latent heat fluxes (bottom panel) in the 2xCO_2, Solar and Stabilized experiments relative to the Control. The lapse rate in the 2xCO_2 (Solar) case increases (decreases). The large stratospheric cooling in the 2xCO_2 case is not mitigated by Solar. As evidenced by reduced evaporation, particularly in the tropics, the hydrologic cycle is weakened in the Stabilized case relative to the control.

Figure 3 Differences in surface energy fluxes, averaged globally and annually, in the 2xCO_2, Solar, and Stabilized cases, relative to Control. "Sfc.net SW" refers to the net surface absorption (incident minus reflected) of solar radiation, and "Sfc. net LW" refers to net absorption (downward minus upward) of longwave radiation at the surface. "Sfc. net radiative" represents the change in the absorbed total radiative flux at the surface. The changes in surface latent and sensible heat fluxes are positive upward.

Table 1 Differences in global- and annual-means of key climate variables in the 2xCO_2, Solar and Stabilized cases, relative to Control. The last row is the sum of the 2xCO_2 and Solar cases.

Experiment	Surface Temp. (K)	Water Vapor (%)	Precip. (%)	[1]Net LW flux TOA (Wm^{-2})	[2]Net SW flux TOA (Wm^{-2})	[3]Net Flux TOA (Wm^{-2})
2xCO_2	2.42	15.2	3.7	-0.54	0.46	-0.08
Solar	-2.40	-15.2	-5.8	4.86	-4.79	0.07
Stabilized	0.14	-2.0	-1.7	3.62	-3.63	-0.01
2xCO_2 + Solar	0.02	0.0	-2.1	4.32	-4.33	-0.01

[1] Net Longwave (downward is positive) at the top of the atmosphere (TOA).

[2] Net shortwave (downward minus upward) at the top of the atmosphere. Downward is positive.

[3] Net flux at the top of the atmosphere is the sum of net LW and net SW fluxes.

Figure 1

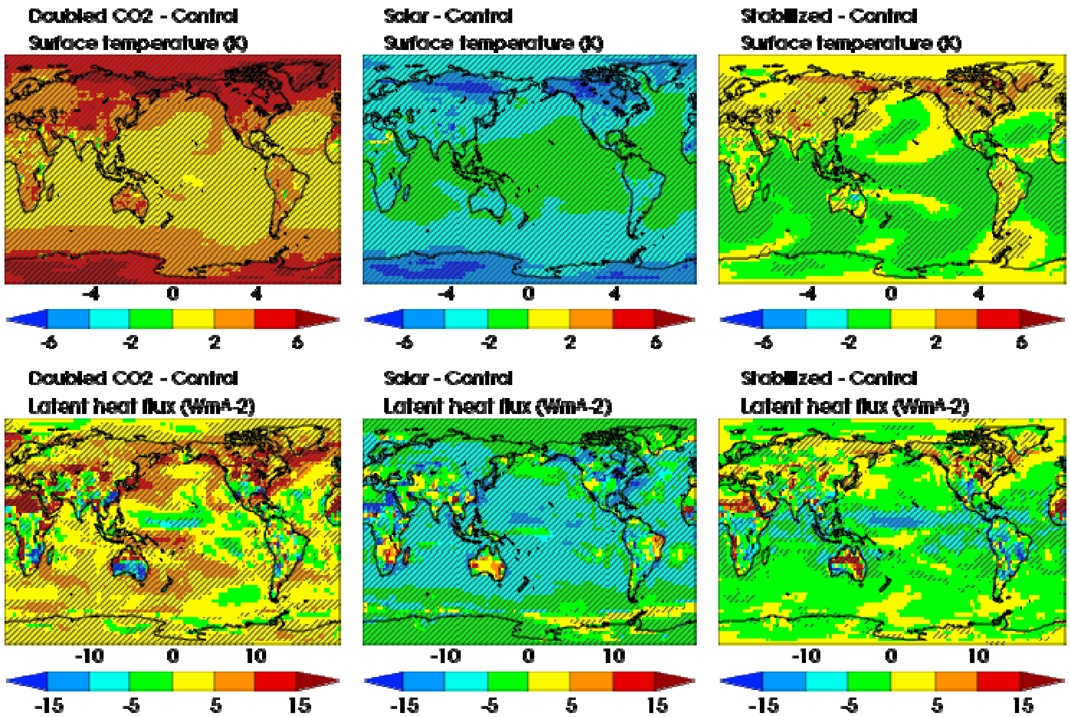

Doubled CO2 - Control
Surface temperature (K)
-4
0
4
-6
-2
2
6
Solar - Control
Surface temperature (K)
-4
0
4
-6
-2
2
6
Stabilized - Control
Surface temperature (K)
-4
0
4
-6
-2
2
6
Doubled CO2 - Control
Latent heat flux (Wm^-2)
-10
0
10
-15
-5
5
15
Solar - Control
Latent heat flux (Wm^-2)
-10
0
10
-15
-5
5
15
Stabilized - Control
Latent heat flux (Wm^-2)
-10
0
10
-15
-5
5
15

Figure 2

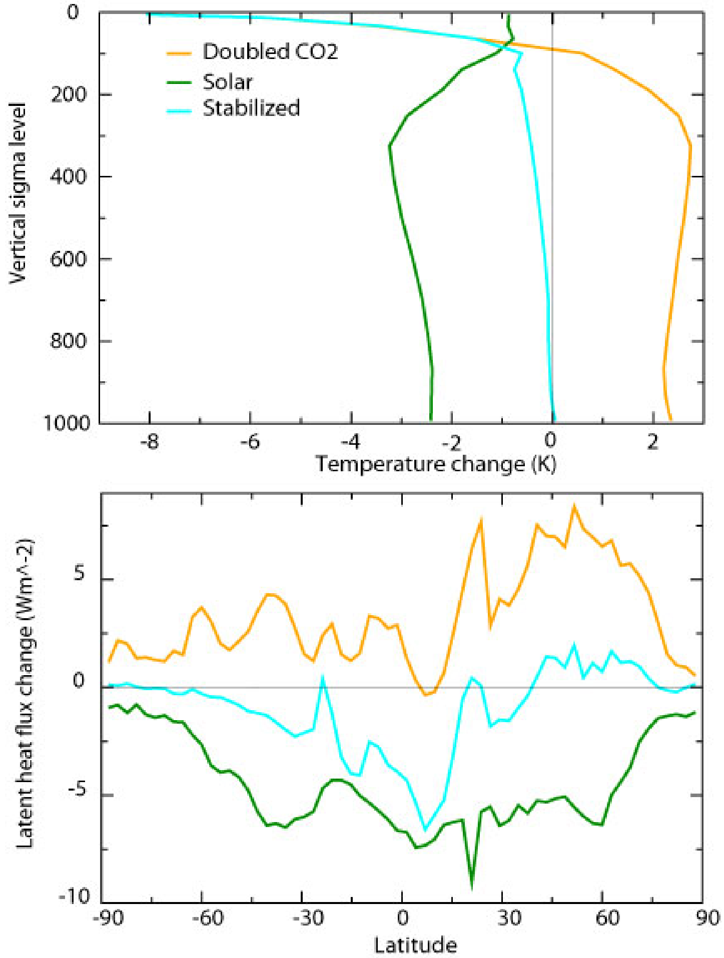
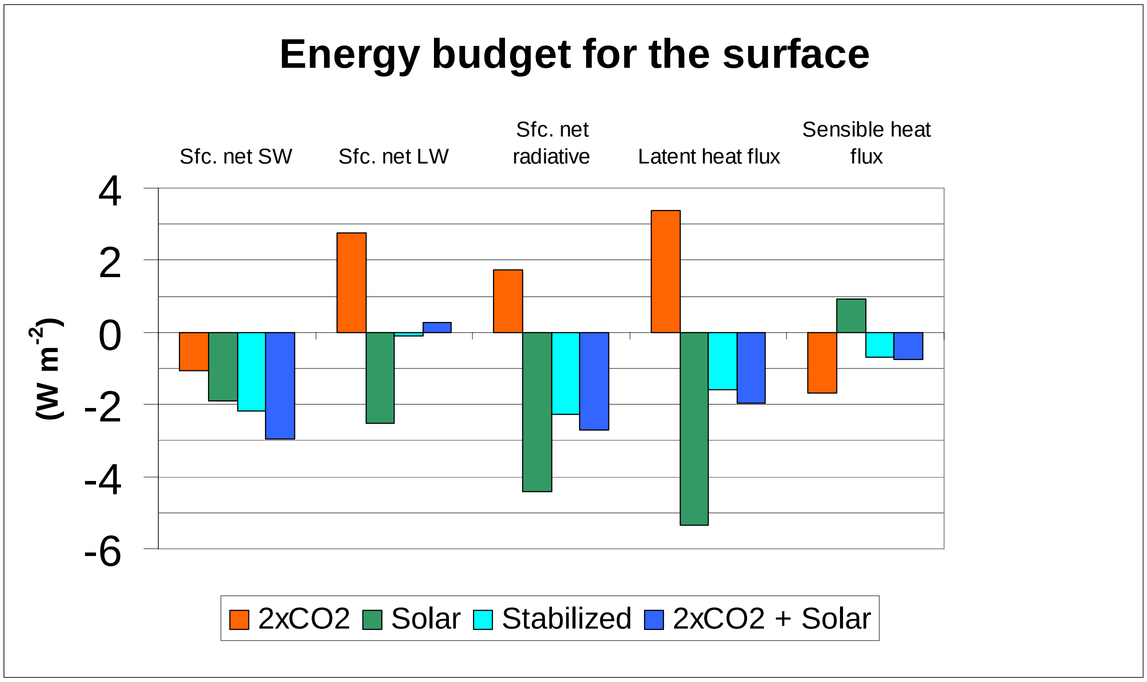

Doubled CO2
Solar
Stabilized
Vertical sigma level
Temperature change (K)
Latent heat flux change (Wm^-2)
Latitude

Figure 3


Energy budget for the surface
Sfc. net SW
Sfc. net LW
Sfc. net radiative
Latent heat flux
Sensible heat flux
4
2
0
-2
-4
-6
(W m-2)
2xCO2
Solar
Stabilized
2xCO2 + Solar