

Impact of geoengineering schemes on the global hydrological cycle

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The rapidly rising CO₂ level in the atmosphere has led to proposals of climate stabilization by “geoengineering” schemes that would mitigate climate change by intentionally reducing solar radiation incident on Earth’s surface. In this article we address the impact of these climate stabilization schemes on the global hydrological cycle. By using equilibrium climate simulations, we show that insolation reductions sufficient to offset global-scale temperature increases lead to a decrease in global mean precipitation. This occurs because solar forcing is more effective in driving changes in global mean evaporation than is CO₂ forcing of a similar magnitude. In the model used here, the hydrological sensitivity, defined as the percentage change in global mean precipitation per degree warming, is 2.4% K⁻¹ for solar forcing, but only 1.5% K⁻¹ for CO₂ 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. For the same surface temperature change, insolation changes result in relatively larger changes in net radiative fluxes at the surface; these are compensated by larger changes in the sum of latent and sensible heat fluxes. Hence, the hydrological cycle is more sensitive to temperature adjustment by changes in insolation than by 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.

climate change | global hydrology | radiative forcing | mitigation

The rapid rise in the rate of fossil fuel emission in recent years has revived the discussion of mitigating climate change by “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 because of the increase in the atmospheric CO₂ and other greenhouse gases (1, 5–12). The other class of schemes typically removes the atmospheric CO₂ and sequesters it in terrestrial vegetation, in deep geologic formations, or in the oceans.

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 if the model configuration is designed such that the incoming solar radiation (“insolation”) is reduced by an appropriate percentage, it could largely mitigate even regional and seasonal climate change from a doubling or quadrupling of CO₂, 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 caused by CO₂ 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 CO₂-induced changes in Net Primary Productivity (NPP) or biomass. Concerns have also been raised that CO₂

effects on ocean chemistry could have deleterious consequences for marine biota because of ocean acidification that is not mitigated by the geoengineering schemes (16).

Investigations of transient climate response to geoengineering by 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 rapid climate change, with warming rates up to 20 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 after the eruption of Mount Pinatubo in 1991. It cautions that a weakened hydrological cycle, including droughts, could arise from geoengineering solutions.

Modeling studies indicate a decline in precipitation in the geoengineered climate (13, 15, 17), relative to an unperturbed control climate. Until now, this decline in precipitation has gone largely unnoticed and has not been investigated in detail. Thus, there has been little recognition of why there should be a reduction in global mean precipitation in the geoengineered climate while there is mitigation in terms of surface temperature change. Larger changes in precipitation for volcanic forcing have been also evident, but not discussed, in earlier modeling studies when the simulated surface temperature changes are the same for CO₂ and volcanic forcing (19). There has also been discussion of how the availability of energy, not moisture, controls the overall intensity of the hydrological cycle (20–22)

Our article investigates the sensitivity of the global mean precipitation to CO₂ and solar forcings separately and explains the causes for the weakening of the global hydrological cycle in a geoengineered world in which global temperature change has been prevented. We analyze existing equilibrium simulations (15). We emphasize that equilibrium simulations can, in general, 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 versus greenhouse forcing—is fundamental and can be understood through a straightforward analysis of the global energy budget.

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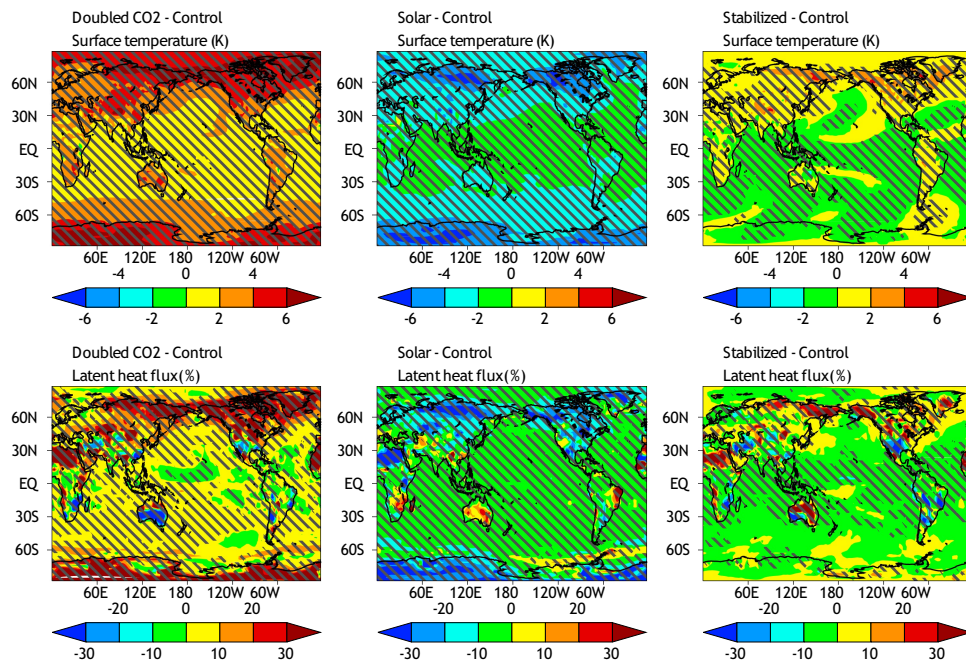


Fig. 1. Changes in annual-mean surface temperature (*Top*) and surface latent heat fluxes (*Bottom*) in the $2\times\text{CO}_2$, solar, and stabilized cases relative to the control. Hatching indicates the regions where the changes are significant at the 1% level. Significance level was estimated by using a Student *t* test. Temperature changes are large and significant everywhere in the $2\times\text{CO}_2$ and solar cases. Although significant over large regions, temperature changes are small in the stabilized case. Surface latent heat flux changes are significant over $>61\%$ and 83% the globe in the $2\times\text{CO}_2$ and solar cases. There is a general decrease in latent heat flux over most of the regions in the stabilized case relative to the control, suggesting that geoengineering will lead to a weakened hydrological cycle.

To make sense of the global mean changes in precipitation, our approach will be to consider how changes in surface latent heat flux are constrained by the surface energy budget in the global mean. First, however, it is helpful to examine briefly the changes in the annual mean and the seasonal variations of the pattern of latent heat flux (Figs. 1 and 2*b* and Fig. S2). In the $2\times\text{CO}_2$ case the latent heat flux generally increases, with larger enhancements in the Northern Hemisphere high-latitude land regions (Figs. 1 and 2*b*). The latent heat flux decreases in the solar case with the magnitude of the reductions being larger than the increases in the $2\times\text{CO}_2$ case in the tropics and Southern Hemisphere (Figs. 1 and 2*b*). We find that the percentage changes in evaporation over land are highly variable with $>30\%$ changes in the high latitudes and $<10\%$ changes in the low latitudes in the $2\times\text{CO}_2$ and solar cases. The changes are rather uniform over oceans at $<10\%$. The evaporation changes shown in Fig. 1 are significant at the 1% level for $>61\%$ and 83% of the globe in the $2\times\text{CO}_2$ and solar experiments, respectively. In the stabilized case, a general decline in latent heat fluxes is evident with statistically significant reductions found mostly in the tropics. Some local increases are seen in high-latitude land regions. Overall, the changes in this case are significant at the 1% level for $>42\%$ of the globe, mostly in the tropical region. Changes in the stabilized case show little seasonal variation (Fig. S2), a result that is in agreement with earlier studies (13).

The changes described above are clearly not uniform spatially, and this is also true of the pattern of precipitation changes, which in many areas bear little resemblance to the evaporation changes (Fig. 1 and Fig. S1). Land–ocean contrasts are evident in the responses of both precipitation and evaporation (Table S1), with the fractional responses over land being larger, especially in the $2\times\text{CO}_2$ case. At smaller than global scale, it is difficult to see similarities in the rather noisy patterns of change in precipitation and latent heat flux.

Why are the hydrological sensitivities different for greenhouse versus solar forcing? Differences in the vertical distribution of

radiative forcing for $2\times\text{CO}_2$ and solar cases (30) lead to a simple explanation. Radiative forcing by CO_2 mainly heats the troposphere (in a direct sense), whereas solar forcing mainly heats the surface (30). 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. This leads directly to the reduced evaporation and precipitation in the stabilized case.

A rigorous 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:

$$\Delta R + \Delta S - \Delta L - \Delta H = 0, \quad [1]$$

where ΔR , ΔS , ΔL , and ΔH represent the differences in longwave radiation, shortwave radiation, latent heat, and sensible heat, respectively. Here, we use this formulation to assess changes in the $2\times\text{CO}_2$, solar, and stabilized cases relative to the control case. 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 relatively fast radiative responses unrelated to changes in global temperature (31)]. Then Eq. 1 becomes

$$F + \Delta R_r + \Delta S_r - \Delta L - \Delta H = 0, \quad [2]$$

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 is approximately $-3 \text{ W}\cdot\text{m}^{-2}$ in the solar case, but only a few tenths of a $\text{W}\cdot\text{m}^{-2}$ in the $2\times\text{CO}_2$ case. Because, to a good approximation, the radiative responses are independent of the forcing mechanism (30), ΔR_r has the same

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 (to a first approximation). The differences in surface radiation in these two cases lead to different responses in evaporation and, consequently, also in precipitation.

The conclusions reached here rest on the approximate validity of Eq. 3, in which radiative responses at the surface are neglected when surface temperature does not change. At the top of the atmosphere (TOA), it is known from modeling studies (30–33) that the radiative response is approximately linearly related to the global mean surface temperature change. This is, in fact, why, when the radiative forcing is carefully defined (31), a model's equilibrium climate sensitivity (i.e., the ratio of global mean temperature change to the global mean forcing) is approximately independent of the characteristics of the forcing (e.g., spatial or temporal pattern). Because the vertical profiles of temperature, humidity, and clouds determine both the surface and TOA radiative fluxes, it would be surprising if one were to change but the other did not. The generally accepted empirical result that the TOA radiative response is a function of the global mean surface temperature implies, therefore, that the surface radiative response will be small if the surface temperature does not change. Thus, Eq. 3 should hold across models, as should our conclusions.

Our results are also consistent with earlier modeling experiments that showed a decrease in precipitation for an increase in atmospheric CO₂ when SSTs were fixed (34, 35). This response 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 because of the CO₂ forcing is balanced by a reduction in latent heat release (reduced precipitation), since the radiative response of the system must be small because of the fixed SST constraint. At the surface, in these experiments, the ocean serves as an infinite heat sink, taking up sufficient heat to balance reduced cooling by evaporation.

Because the model used here lacks a dynamic ocean and sea ice model, the transient effects of climate change and its impact on global hydrology are not assessed in this study. It is possible, however, to apply our analysis to a hypothetical transient simulation in which temperature changes that would result from gradual increases in greenhouse gases were successfully mitigated (in terms of global mean temperature) by gradual increases in sulfate aerosol concentrations, for example. Under these conditions the climate might not remain in true equilibrium because some regions might warm whereas others might cool (although the global mean would not change). There could also be exchanges of heat with the oceans. To the extent Eq. 3

holds, as applied to the atmosphere, we would expect to find a gradual decrease in the global mean precipitation rate, consistent with our equilibrium theory.

The differing hydrological 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. Although these schemes could possibly mitigate, to a degree, the harmful effects of rising surface temperature, they will lead to a reduction in global mean precipitation and evaporation.

Our investigation has focused only on the *global* hydrology; we have not analyzed regional details of hydrological changes caused by geoengineering because, in all cases, the changes in precipitation are quite small relative to interannual variability at the regional scale (Fig. S1). We find, for example, that for a doubling of CO₂, the precipitation changes are significant at the 1% level over only 46% of the globe. For the stabilized case, this fraction drops to 33%. Precipitation minus evaporation ($P - E$) is an approximate measure of water availability and droughts. Statistical significance of changes in this quantity is achieved over only 25% of the globe in the stabilized case (Fig. S1). Longer integrations and high-resolution modeling will be required to provide confidence in regional scale changes in runoff, soil moisture, streamflow, and water resources. We also have not investigated daily and hourly rates (i.e., intensity) of precipitation, although there is evidence that climate change will affect the frequency and intensity of storms, with changes in precipitation intensity within individual storms expected to scale with changes in atmospheric water vapor content (20, 29).

Besides a reduction in the rate of global mean water cycling 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 because the geoengineered world would still have higher concentration of atmospheric CO₂. Some stabilization schemes could adversely impact the ozone layer. CO₂-induced climate change would last multiple centuries because the atmospheric residence time scale of CO₂ is a few centuries. Consequently, 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 (36), and technical failure of a stabilization scheme could be catastrophic (17).

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