Intensity of Hydrological Cycles in Warmer Climates

FANGLIN YANG
NASA Goddard Space Flight Center, Greenbelt, Maryland

ARUN KUMAR
National Centers for Environmental Prediction, Climate Prediction Center, Washington, D.C.

MICHAEL E. SCHLESINGER
Department of Atmospheric Sciences, University of Illinois at Urbana–Champaign, Urbana, Illinois

WANQIU WANG
National Centers for Environmental Prediction, SAIC/Environmental Modeling Center, Washington, D.C.

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ABSTRACT

The fact that the surface and tropospheric temperatures increase with increasing CO_2 has been well documented by numerical model simulations; however, less agreement is found for the changes in the intensity of precipitation and the hydrological cycle. Here, it is demonstrated that while both the radiative heating by increasing CO_2 and the resulting higher sea surface temperatures contribute to warm the atmosphere, they act against each other in changing the hydrological cycle. As a consequence, in a warmer climate forced by increasing CO_2 the intensity of the hydrological cycle can be either more or less intense depending upon the degree of surface warming.

1. Introduction

In the 2001 Intergovernmental Panel on Climate Change (IPCC) report (Houghton et al. 2001), 19 coupled ocean–atmosphere general circulation models (GCMs) that participated in the second phase of the Coupled Model Intercomparison Project (CMIP2; Meehl et al. 2000) were used to project future climate changes. All these models were forced with an idealized forcing, namely, a 1% yr^{-1} compound increase of CO_2. For the 20-yr period centered on the time of CO_2 doubling (years 61–80), global surface temperature increased by 1.1°–3.1°C relative to the control runs in which CO_2 was kept constant, with an average increase of 1.8°C and a standard deviation of 0.4°C. For precipitation, the percentage change ranged from −0.2% to 5.6%, with an average of 2.5% and a standard deviation of 1.5% (Houghton et al. 2001; Räisänen 2002).

While the IPCC report concluded that both globally averaged temperature and precipitation will increase in the twenty-first century, the model simulations in CMIP2 indicate that the relationship between the intensity of the hydrological cycle and warmer climates may not be very robust. In some extreme cases, warmer climates may be associated with a decrease in the hydrological cycle intensity. Large uncertainties in the change of the intensity of the hydrological cycle in warmer climates have also been reported in many other GCM simulations (e.g., Allen and Ingram 2002; Boer et al. 2000; Roeckner et al. 1999; Watterson 1998; Wild et al. 1997). Why is the influence of increased CO_2 in the different GCMs more consistent on temperature than on precipitation and the hydrological cycle?[1] Should precipitation and the hydrological cycle necessarily be more intense in warmer climates?

Based on heuristic arguments, on a global mean basis, equilibrium atmospheric temperature is maintained by a balance between radiative cooling and condensational heating. Any small perturbation in either can lead to a drift in the time-mean atmospheric temperature. The atmosphere will eventually adjust itself to a new steady state. The question is whether there is a well-defined directional relationship between the change in atmo-

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Corresponding author address: Dr. Fanglin Yang, NASA Goddard Space Flight Center, Code 913, Greenbelt, MD 20771.
E-mail: fyang@climate.gsfc.nasa.gov

[1] Hydrological cycle defines the circulation of water throughout the earth system. It usually includes evaporation, precipitation, and runoff. Globally averaged, annual mean evaporation is balanced by annual mean precipitation.

TABLE 1. Responses in global means to anomalous CO_2 or SST forcing simulated by the NCEP GCM. Here T represents tropospheric temperature in K, which is the mass-weighted mean air temperature from the surface to 200 hPa. The calculation was carried out at each model grid point before global means were derived. Here Pr is precipitation in mm day^{-1}. Shown in the parentheses are the equivalent condensational heating in W m^{-2}. LW and SW are terrestrial and solar radiation, respectively, absorbed by the atmosphere (W m^{-2}). LH and SH are latent and sensible heat fluxes, respectively, from the earth's surface to the atmosphere (W m^{-2}). The WV is the column-integrated water vapor amount in the atmosphere (kg m^{-2}). CLD is cloud cover in percent. On a global annual mean basis the change in the energy components in and out of the atmosphere (LW+SW+LH+SH) is almost balanced. Condensational heating from precipitation matches the surface latent heat flux associated with evaporation because in principle annual precipitation is balanced by evaporation. For all experiments the change in atmospheric radiative cooling (LW) is primarily balanced by anomalous condensational heating (Pr or LH), and compensated by changes in SH and SW. Changes in cloud cover and water vapor are included to illustrate the feedbacks involved in the atmospheric adjustments to new steady states.

	T	Pr	LW	SW	LH	SH	WV	CLD
2 × CO_2	0.22	−0.075 (−2.17)	2.23	0.17	−2.16	−0.22	0.22	−0.14
0.5 × CO_2	−0.16	0.051 (1.47)	−1.75	−0.14	1.47	0.47	−0.22	0.19
SST+1	1.43	0.102 (2.95)	−4.02	1.11	2.92	0.04	2.44	0.72
SST−1	−1.38	−0.113 (−3.26)	4.15	−1.12	−3.25	0.21	−2.25	−0.71

spheric temperature and the change in the intensity of precipitation. For the case of a temperature perturbation initiated by a reduction in radiative cooling (e.g., due to an increase in CO_2), a possible pathway for the atmosphere to adjust toward a new steady state of higher temperature is by a decrease in condensational heating and a corresponding reduction in precipitation. On the other hand, for the case of a temperature perturbation initiated by an enhancement in condensational heating, for instance, due to increased sea surface temperatures (SSTs), the atmosphere can adjust itself to a new steady state through an increase in radiative cooling. For both cases, although the new steady-state atmospheric temperature is higher, the changes in the hydrological cycle are in opposite directions. This energy-based argument is, of course, an oversimplification of different physical processes active in the atmosphere. Various nonlinear adjustments (e.g., changes in the distribution of cloud amounts) may lead to a final equilibrium state that deviates from what one can expect based only upon above arguments.

The hypothesis is tested using a set of GCM experiments. It is demonstrated that, at least for the GCM used in this study, results for the adjusted equilibrium state can be interpreted within the framework of the above simple argument. It is also shown that the influence of increased CO_2 in the different GCMs on the intensity of the hydrological cycle largely depends on the degree of sea surface warming, and further, the hydrological cycle need not be more intense in a warmer climate.

2. Numerical experiments and results

a. *Precipitation intensity under different forcing scenarios*

We first performed two sets of idealized model experiments to examine the precipitation intensity under different forcing scenarios. The model used is the National Centers for Environmental Prediction (NCEP) global spectral model (Kanamitsu et al. 2002). The model has a spectral triangular truncation at horizontal wavenumber 42 (T42) and has 28 levels in the vertical direction. In the first set of experiments, the CO_2 concentration was set to either two times or half its present value, but the SSTs were prescribed to an observed climatology (Reynolds and Smith 1994). In the second set of experiments, the SSTs were either increased or decreased by 1.0 K everywhere over the oceans, but the CO_2 concentration was kept constant at its present level. A control run was also performed with present CO_2 and the observed SST climatology. All experiments started from the same initial conditions and were integrated for 6 yr. These experiments allow us to assess how the hydrological cycle responds to the two types of perturbations: radiative due to changes in CO_2 and condensational due to changes in SSTs. We should point out that similar experiments can be conducted to test our hypothesis with other types of radiative forcing, such as anthropogenic aerosols, black carbon, changes in solar constant, and so on.

Changes in global annual mean temperature and precipitation from these experiments relative to the control run are summarized in Table 1. A few other quantities related to the energy budget and feedbacks in the atmosphere are also included. For both experiments 2 × CO_2 and SST+1, tropospheric temperature increased; however, precipitation decreased in the former and increased in the latter. For the experiment 2 × CO_2, increased CO_2 trapped more outgoing longwave radiation, enhanced the tropospheric radiative heating (i.e., a reduction in longwave radiative cooling), and initiated a tropospheric warming. The atmosphere adjusted to a new state by reducing precipitation (and hence condensational heating) to offset the reduced radiative cooling. In contrast, for the experiment SST+1, higher SSTs caused precipitation to intensify. Stronger condensational heating associated with precipitation warmed the atmosphere (Fu et al. 1994). The atmosphere adjusted to a new state by the increase in radiative cooling. A comparison between the experiments 0.5 × CO_2 and SST-1 demonstrated almost the same adjustments and feedbacks as above, but with the changes in opposite directions.

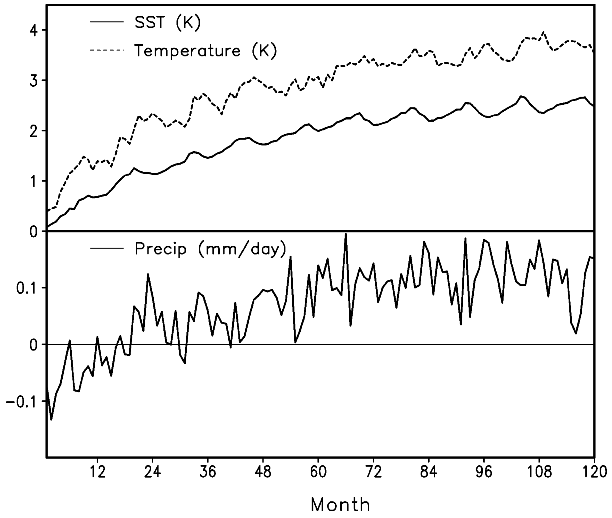

FIG. 1. Changes in global monthly mean SST, tropospheric temperature, and precipitation during the first 10 yr of a coupled ocean–atmosphere CO_2 doubling experiment. For each variable, the change was defined as the departure from the 10-yr average of monthly global means of the control ($1 \times CO_2$) experiment. Both experiments were performed using the UIUC 11-layer GCM coupled to a mixed layer ocean model. Global mean SST was computed using data over open ocean points. The method described in Table 1 was used to calculate the tropospheric temperature.

b. Evolution of precipitation intensity in an instantaneous $2 \times CO_2$ experiment

In a coupled ocean–atmosphere system forced by increasing CO_2, because of the large thermal inertia of the ocean, changes in the oceanic temperature occur on a much slower timescale compared to the changes in the atmospheric temperature. Results from the above experiments, therefore, suggest that the influence of any changes in the CO_2 on the hydrological cycle will also occur on two different timescales. On the fast timescale, the direct radiative effect of increasing CO_2 will lead to a reduction in the hydrological cycle. On the slower timescale, the indirect influence of increasing CO_2, via an increase in oceanic temperature, will lead to an increase in the intensity of the hydrological cycle. Because of their competing influences on the hydrological cycle, trends in the hydrological cycle may have a more complex behavior than the trends in the atmospheric temperature. This is demonstrated in a doubling CO_2 experiment performed with the University of Illinois at Urbana–Champaign (UIUC) 11-layer GCM coupled to a mixed layer ocean model (Schlesinger et al. 2000). The doubling of CO_2 was instantaneous, that is, at the beginning of the experiment CO_2 was set to 2 times its present value and kept constant.

We examine the time evolution of the simulated changes in tropospheric temperature, SST, and precipitation in the first 10 yr of the simulation (Fig. 1). After the CO_2 concentration was doubled, tropospheric temperature increased as a result of the CO_2 radiative heating. However, precipitation was reduced. At the beginning, SSTs did not increase significantly, and as expected, their response was delayed compared to the tropospheric temperature because of the large thermal inertial of the ocean. As SSTs gradually increased, precipitation also started to increase, and eventually overcame the reduction of precipitation due to the direct radiative influence of CO_2. Therefore, in contrast to a steady warming trend in the atmospheric temperatures, the trend in precipitation indeed demonstrated a more complex behavior.

c. Dependence of hydrological cycle intensity on model sensitivity to CO_2 doubling

The analysis presented so far points to a possible cause for the large uncertainty in the estimates of the changes in the hydrological cycle found in the CMIP2 1% yr^{-1} CO_2 increase experiments (Meehl et al. 2000; Räisänen 2002). This uncertainty can result in part from the competing influences of increasing CO_2 on the hydrological cycle: the direct radiative influence of CO_2 tends to reduce the intensity of the hydrological cycle; its indirect influence, via the increase in the oceanic temperature, leads to a more intense hydrological cycle. In contrast, the influence of both factors on the tropospheric temperature is in the same direction, leading to a more consistent trend for the atmospheric temperature. An obvious cause that can lead to different intensity of the hydrological cycle in the models is that, because of their different sensitivity to CO_2 doubling, the coupled models may differ in their simulated oceanic warming (Hansen et al. 1984; Houghton et al. 2001; Mitchell et al. 1987). For models with small sensitivity, the increase in precipitation associated with the oceanic warming will also be small, and for the models with large sensitivity, changes in the precipitation will be large. For the models with small sensitivity the increase in precipitation may not exceed the reduction in precipitation due to the direct influence of increased CO_2 radiative heating, leading to a net reduction in precipitation for increased CO_2.

The empty circles in Fig. 2 show global annual mean precipitation changes versus the corresponding surface temperature changes centered at the time of CO_2 doubling simulated by the 19 CMIP2 models. As expected, for models with small changes in surface temperature, that is, small sensitivity to CO_2 doubling, the changes in precipitation were small. However, the distribution also has a large scatter around a quasi-linear relationship between the two, and for a fixed change in the surface temperature anomaly, the change in precipitation can differ by a large amount among different models. There are two possible causes: 1) for the same surface warming, different models may differ in their simulations of precipitation change because of different parameterization schemes employed; and 2) the influence of the direct effect of radiative forcing due to changes in CO_2

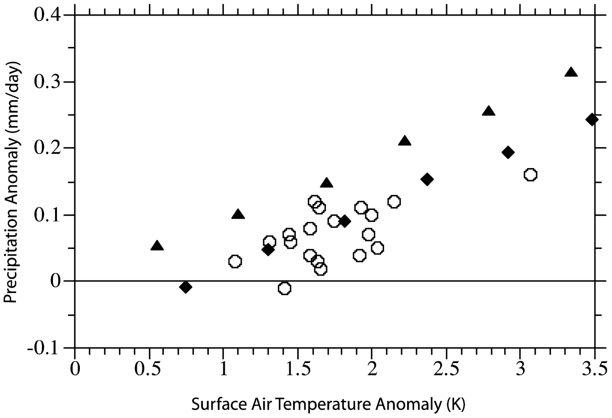

FIG. 2. Changes in global annual mean precipitation vs changes in surface temperature. Open circles are for the 20-yr averages centered at the time of CO_2 doubling simulated by 19 CMIP2 coupled models. Solid triangles are for the 5-yr averages of six 1 × CO_2 experiments simulated by the NCEP global spectral model forced by six different prescribed SST anomalies. Solid diamonds are the same as the triangles except that in the experiments CO_2 concentration was doubled. From left to right, the triangles and diamonds correspond to SST anomalies of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 K, respectively.

on the hydrological cycle may also differ among the different GCMs.

To demonstrate that for a fixed set of parameterization schemes the dependence of net precipitation change on surface warming will indeed be much more linear, we performed six idealized CO_2 doubling experiments using a single GCM, the NCEP global spectral model (Kanamitsu et al. 2002). In these experiments the CO_2 concentration was set to 2 times its present value, and the climatological SSTs (Reynolds and Smith 1994) were increased by 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 K, respectively (see the solid diamonds in Fig. 2). All experiments started from the same initial conditions and were integrated for 6 yr. To further show how the changes in CO_2 affect the relationship between SST warming and the intensity of precipitation, simulations were repeated with the present amount of CO_2 concentration (solid triangles in Fig. 2). Changes in global annual mean precipitation and surface temperature relative to the control run, which was carried out with the present CO_2 and climatological SSTs, were derived and averaged for the last 5 yr of the simulations. This type of idealized CO_2 doubling experiment has been used before (e.g., Mitchell et al. 1987) to study climate changes induced by CO_2 doubling. It serves as a surrogate for the fully coupled ocean–atmosphere GCM experiment that usually requires hundreds of years of simulations for models to reach quasi-equilibrium.

Indeed, for a fixed CO_2 amount, the change in precipitation depends rather linearly on the surface warming (Fig. 2). Such a quasi-linear dependence of precipitation on surface warming was also found by Sokolov et al. (2001) in the Massachusetts Institute of Technology (MIT) zonally averaged statistical–dynamical atmospheric model. It is also noteworthy that the rate of precipitation increase for 2 × CO_2 experiments is smaller than that for the 1 × CO_2 simulations, and the difference between the two is indicative of the suppressing effect of the direct radiative forcing of increased CO_2 on the precipitation for this GCM. The strength of this effect is likely to vary among different GCMs. This is possibly one reason among others why for a fixed surface warming, precipitation changes among different models have a large spread.

It is interesting to note that for the experiment in which SSTs were increased by only 0.5 K, the net change in precipitation is negative (Fig. 2); that is, the expected increase in precipitation associated with the surface warming did not exceed the reduction in precipitation related to the direct CO_2 radiative heating. We should also point out that the precipitation changes simulated by the single NCEP model fell within the range of precipitation changes simulated by 19 different CMIP2 models.

3. Conclusions

In this study, starting from a simple energy budget argument, that is, equilibrium atmospheric temperature is maintained by a balance between radiative cooling and condensational heating, we demonstrated that warmer climates can be associated with either an increase or a decrease in the intensity of the hydrological cycle. The association between the changes in the atmospheric temperature and precipitation depends on the forcing perturbation, and the degree to which condensational heating has to adjust to bring the ocean–atmosphere system to a new equilibrium state. The competing influences of the direct CO_2 radiative heating and the resulting surface warming on the hydrological cycle, and the different model sensitivity in the SST warming to CO_2 doubling, may partially explain why in the CMIP2 experiments there is a much larger degree of uncertainty in the estimates of the hydrological cycle compared to a better defined trend of the surface and tropospheric temperature. Results also imply that apart from the difficulty in accurately measuring precipitation over the oceanic regions, the influence of increasing CO_2 on the hydrological cycle may be inherently more difficult to infer than its influence on the atmospheric temperature.

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