NOTES AND CORRESPONDENCE

A Mechanism of Tropical Precipitation Change due to CO₂ Increase

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13 February 2003 and 15 July 2003

ABSTRACT

A recent GCM study indicates that a weakening of tropical circulation associated with a slight increase in tropical precipitation may occur when atmospheric CO₂ is increased. To further understand the mechanism of atmospheric temperature and precipitation changes associated with the greenhouse gas increase, a numerical experiment was conducted using an atmospheric general circulation model to investigate the separate effects of CO₂ increase and sea surface temperature (SST) increase. It has been shown that the effect of CO₂ increase is a reduction of radiative cooling in the lower troposphere, leading to a reduction of tropical precipitation. When atmospheric CO₂ concentration is doubled (quadrupled) without changing the SST, the tropical precipitation is reduced by about 3% (6%) in the model. The reduction of radiative cooling is a result of the overlap effect of the CO₂ 15-μm and water vapor absorption bands. On the other hand, the effect of SST increase is the increase in atmospheric temperature and water vapor, leading to increases in radiative cooling and tropical precipitation. When SST is uniformly raised 2°C without changing the atmospheric CO₂ concentration, the tropical precipitation is increased by about 6%.

1. Introduction

Recent studies with a high-resolution AGCM indicate that a significant reduction of tropical cyclone frequency may occur when greenhouse gas in the atmosphere is increased (Bengtsson et al. 1996; Sugi et al. 2002). These studies have shown that the reduction of tropical cyclone frequency is closely related to a weakening of tropical circulation. Sugi et al. (2002) noted that a significant increase in dry static stability in the troposphere and little increase in tropical precipitation are the main factors contributing to the weakening of tropical circulation. In this regard, it is important to understand why the tropical precipitation increases little in spite of a significant increase in atmospheric moisture.

When the greenhouse gas in the atmosphere is increased, the downward longwave flux at the earth’s surface increases. This causes the increase in surface temperature, and in turn increases atmospheric temperature and water vapor. The increased water vapor further increases the downward longwave flux (water vapor feed-back). To further understand the mechanism of atmospheric temperature and precipitation changes due to greenhouse gas increase, we have conducted a numerical experiment to separate the effect of CO₂ increase and SST increase. The results of the experiment indicate that the overall intensity of tropical precipitation is not controlled by the availability of moisture, but by the availability of energy, as pointed out by Allen and Ingram (2002).

2. Experiments

We have conducted five experiments as shown in Table 1, using the Japan Meteorological Agency Global Atmosphere Model (JMA-GSM8911; Sugi et al. 1990; JMA 1993). The horizontal resolution of the model is T106 (about 120-km mesh). The model has 21 levels in the vertical. The first three experiments use the different SST but use the same atmospheric CO₂ concentration, while the last three experiments use the same SST but a different CO₂ concentration. The SSTs used in the warming (cooling) experiments are uniformly higher (lower) by 2°C than the climatology. The length of model integration for each experiment is 10 yr.
3. Results

The results of the experiments are summarized in Table 2. When the SST is uniformly increased by 2°C without changing the atmospheric CO₂ concentration, tropical precipitation increases by about 6%. The precipitation increase corresponds to the increases in convective heating and radiative cooling (longwave cooling minus solar heating) in the upper troposphere (Fig. 1a). Since the air temperature in the upper troposphere in this case increases more than that in the lower troposphere, the dry static stability also increases when SST is increased (Table 2). These changes in tropical precipitation and dry static stability may be explained by the enhanced tropical convection associated with the increased atmospheric moisture. It should be noted that in this case the solar heating considerably increases due to increased atmospheric moisture.

On the other hand, as shown in Table 2, when the atmospheric CO₂ concentration is increased without changing the SST, the tropical precipitation is significantly reduced. Temperature and dry static stability do not change much in this case. Although the reduction of tropical precipitation due to CO₂ increase has been found by some previous studies (Mitchell 1983; Tokioka and Saito 1992), the reason for the reduction of precipitation has not yet been fully understood. From Fig. 1b the reason for the reduction of tropical precipitation seems to be the reduction of longwave radiative cooling in the tropical lower troposphere. Figure 1b shows the changes in the radiative and convective heating rates due to the CO₂ increase. The radiative heating increases in the lower troposphere. Almost the same amount of reduction occurs in the convective heating. This indicates that the increase in the radiative heating (reduction in longwave cooling) associated with the CO₂ increase causes the reduction of tropical convective heating (precipitation). It should be noted that in this case the change in solar heating is very small, indicating that the change in atmospheric water vapor or cloud is little, and the change in longwave cooling is not due to the change in water vapor or cloud but directly due to the CO₂ increase.

The reduction in the longwave cooling in the tropical lower troposphere, however, is not simply explained by the greenhouse effect of CO₂ alone. This is indeed a result of the overlap effect of the CO₂ 15-μm and water vapor absorption bands. Therefore, the coexistence of CO₂ and water vapor is essential for the reduction of
Fig. 2. Atmospheric heating rate due to longwave radiation in the spectral band 550–800 cm$^{-1}$ for a tropical atmosphere. (top) Water vapor only. (middle) CO$_2$ only. (bottom) The overlap effect of CO$_2$ and water vapor bands is considered. Solid lines indicate the calculation using 1D version the radiation code used in the JMA-GSM8911 model. Dashed lines indicate the line-by-line calculation (Shibata and Aoki 1998). These computations are made using a tropical standard atmosphere (McClatchey et al. 1972) without any feedback.

4. Discussion

The reduction of radiative cooling rate due to the overlap effect of CO$_2$ and water vapor bands is well known (Ohring and Joseph 1978). The reduction of longwave cooling due to the overlap effect in the lower tropical troposphere associated with CO$_2$ doubling has also been pointed out (Kiel and Ramanathan 1983; Mitchell et al. 1987; Shibata and Aoki 1989). The amount of reduction due to the overlap effect of longwave cooling in the lower troposphere in the Tropics is about 0.1 K day$^{-1}$ (Kiehl and Ramanathan 1983), and close to the heating rate change shown in Fig. 1b. This indicates that the reduction in the radiative cooling in the GCM experiment is mostly explained simply by the overlap effect, although many other complicated processes, such as land–ocean contrast and cloud–radiation feedback, etc., could be involved.

The reduction of precipitation when CO$_2$ is increased without changing SST has been noted in some other
GCM experiments (Mitchell 1983; Tokioka and Saito 1992), and some explanations have been proposed. First, when CO$_2$ is increased, the land surface temperature increases even though the SST is fixed. The lower atmosphere becomes warmer, thereby increasing low-level static stability over the ocean and reducing precipitation (Mitchell 1983). However, our experiment indicates that the dry static stability shows very little change when CO$_2$ is increased without changing SST (Table 2). Therefore, the static stability change does not explain the reduction of precipitation. Second, because the land surface temperature increases when CO$_2$ is increased without changing SST, an anomalous low may develop over the land, producing an anomalous rising motion over the land and subsidence over the ocean, which may suppress precipitation over the ocean (Tokioka and Saito 1992). This explanation, however, does not quantitatively explain the reduction of precipitation, nor does it explain the reduction in the radiative cooling rate in the lower troposphere as shown in Fig. 1b. Moreover, the reductions in the radiative cooling and convective heating similar to Fig. 1b have also been noted in a one-dimensional radiative convective model experiment in which there is no land–ocean contrast, although no explanation was given of the reason for reduction (Takata and Noda 1997).

In this study, we have shown a significant reduction of tropical precipitation due to CO$_2$ increase. It may be important to note that the reduction of tropical precipitation (convection) is closely related to the reduction of...
of radiative cooling in the atmosphere. This balance between radiative cooling and convective heating in the Tropics is not surprising, because they should be approximately balanced in the equilibrium climate state. When SST is increased without changing CO₂ (Fig. 1a), the change in radiative cooling seems to be a result of the change in temperature and water vapor associated with the increased convection. On the other hand, when CO₂ is increased without changing SST (Fig. 1b), it seems that atmospheric radiative cooling changes first, and the reduction of precipitation follows it (“radiative control of tropical precipitation”). The idea of radiative control of precipitation is not new (Allen and Ingram 2002), but our experiment provides a clear example to support this mechanism.

Another important point may be that the reduction of radiative cooling associated with the CO₂ increase is a result of overlap effect of CO₂ and water vapor absorption bands and the coexistence of CO₂ and water vapor in the earth’s atmosphere is essential. The effect of CO₂ and the other greenhouse gases are not the same in this regard. A simplified treatment of greenhouse gases as CO₂ equivalent may cause a problem in estimating the impact of greenhouse gas increase on the tropical precipitation and the earth’s climate. Since the overlap effect is a unique mechanism in the greenhouse warming due to CO₂ increase, it enables us to distinguish the CO₂-induced climate change from other climate changes. When both CO₂ and SST are increased, as in the real-world global warming, tropical precipitation would increase due to the dominant effect of SST increase (Table 2; WARM2). However, the amount of tropical precipitation increase is considerably reduced by the overlap effect of CO₂ and water vapor (Table 2; WARM2-WARM1). The relatively little increase in tropical precipitation and a significant increase in static stability could cause a weakening of tropical circulation (Sugi et al. 2002). The recent observation shows a strengthening of tropical circulation associated with the decadal variability in the tropical mean radiative energy budget (Chen et al. 2002; Wielicki et al. 2002). The weakening of tropical circulation associated with the little increase in precipitation supports the idea that the recently observed intensification of tropical circulation is not directly caused by the greenhouse warming due to CO₂ increase.

We focused on the Tropics in this paper, but the reduction of precipitation due to the overlap effect of CO₂ and water vapor absorption bands may also occur in the extratropics. To examine this, tropical and global averages of the changes in radiative cooling and convective heating in the experiments are shown in Fig. 3. Both the globally averaged convective heating rate and radiative cooling rate are considerably less than those averaged over the Tropics. It is interesting to note that the change in globally averaged radiative cooling in the SST increase experiment is significantly less than the tropical average, because of much less atmospheric moisture in the extratropics than that of Tropics (Figs. 3a,c). In contrast, the change in globally averaged radiative heating in the CO₂ increase experiment is not significantly less than the tropical average, particularly for the WARM2 experiment (Figs. 3b,d). This suggests that the overlap effect of CO₂ and water vapor absorption bands also works well in the extratropics. Allen and Ingram (2002) proposed a linear relationship between global precipitation and surface temperature when CO₂ is doubled, based on AOGCM experiments including the Second Coupled Model Intercomparison Project (CMIP2) models. The linear relationship suggests that the global precipitation increases 3.4% when surface temperature increases 1°C, while it decreases 4.8% when CO₂ is doubled without changing surface temperature. The globally averaged precipitation in our SST increase experiment increases 3.6% (1°C)−1 SST increase, while the globally averaged precipitation in the CO₂ increase experiment decreases about 4% when CO₂ is doubled. The latter suggests that a major part of the reduction of global precipitation, as well as tropical precipitation, due to CO₂ increase may be explained by the overlap effect of CO₂ and water vapor absorption bands.

**Acknowledgments.** This study was conducted as a part of joint project on Global Warming Research of the Meteorological Research Institute and Frontier Research System for Global Change. The authors would like to express their sincere thanks to Professor S. Manabe for his discussion and encouragement throughout this study.

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