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Tropical Cyclone Climatology in a High-resolution AGCM —Impacts of SST Warming and CO_2 Increase—

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Abstract

Using a high-horizontal-resolution atmospheric general circulation model (AGCM), impacts of SST warming and CO_2 increase on the tropical cyclone (TC) climatology are investigated. The SST effect is examined from numerical experiments in which SST is uniformly higher/lower by 2 K, without changing the atmospheric CO_2 concentration. The CO_2 effect is shown from doubled and quadrupled CO_2 experiments with a fixed SST condition. The results demonstrate that the increases in CO_2 have large impacts to reduce TC frequency globally, while the SST changes have relatively small influences on the TC frequency.

The SST warming causes significant increase in climatological precipitation, and this indicates intensification of convective heating and should have some influences to activate the atmospheric circulation in terms of vertical mass flux in the tropics. In the high-SST experiment, however, larger warming in the upper troposphere causes higher dry static stability, which should have some impacts to weaken the atmospheric circulation. It seems that these two conflicting factors, in terms of TC frequency, may cancel out to a large extent.

As the effect of CO_2 enhancement, precipitation decreases significantly in the tropics, which may lead to the reduction in TC frequency.

1. Introduction

Recent studies with high-resolution atmospheric general circulation models (AGCMs) indicated that frequency of tropical cyclones (TCs) may significantly decrease in response to the global warming (Bengtsson et al. 1996; Sugi et al. 2002; Yoshimura et al. 2004; Oouchi et al. 2005). It is shown that the reduction of TC frequency is closely related to weakening of tropical circulation in terms of vertical mass flux (Sugi et al. 2002). 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.

Sugi and Yoshimura (2004, hereafter SY2004) investigated a mechanism of tropical precipitation change as an impact of CO_2 increase, as well as a separate effect of sea surface temperature (SST) warming. They showed that the effect of CO_2 increase is a decrease of tropical precipitation and the effect of SST warming is an increase of tropical precipitation.

In the present paper, we investigate the separate effects of SST warming and CO_2 increase on TC frequency as simulated in a high-resolution AGCM.

2. Model and experimental design

We have used model output data from a series of numerical experiments (SY2004) as summarized in Table 1. Ten-year integration was executed for each experiment, using a previous version of the JMA Global Spectral Model (GSM8911) as a high-resolution AGCM. The model is configured with horizontal spectral truncation of T106 (equivalent to about 120-km grid spacing), and it has 21 vertical levels. In this model, comprehensive physical processes are included: e.g. radiation (Sugi et al. 1990; Lacis and Hansen 1974) and moist convection (Kuo 1974).

The climatological SST from observation is used as a lower boundary condition for a control experiment (CLIM1). The SST used in a cool-climate experiment (COOL1) is uniformly lower by 2 K than the climatology. In the other three experiments (WARM1, WARM2, and WARM4), SST is uniformly raised by 2 K from the climatology. Atmospheric CO_2 concentration is doubled in WARM2 and quadrupled in WARM4. We used the same sea ice data (climatology from observation) in all of the experiments, because influences of sea ice changes in high latitudes are considered to be small on the TC climatology. Initial conditions of the atmosphere and the land surface for all the experiments were taken from another present-day simulation with the same model.

Influences of the global SST changes by 2 K or 4 K are examined with the same CO_2 concentration from comparisons among COOL1, CLIM1, and WARM1. Impacts of the CO_2 doubling and quadrupling without changing SST are shown by comparisons among WARM1, WARM2, and WARM4. These are expressed as the 'SST effect' and the 'CO_2 effect', respectively, in the present paper.

3. Changes in large-scale fields

Before investigating TCs in the model, we briefly describe time-mean large-scale fields in this section.

SY2004 have found that, as the effect of SST rise, the upper troposphere warms up significantly more than the lower troposphere, and dry static stability, therefore, becomes higher. They have also found precipitation increase in the tropics. Figure 1 shows zonal-mean precipitation and its changes in the 10-year

Table 1. Summary of the numerical experiments. The same as those of SY2004.

Experiment	SST	CO_2 concentration
COOL1	2 K cooling	Normal
CLIM1	Climatology	Normal
WARM1	2 K warming	Normal
WARM2	2 K warming	2 x CO_2
WARM4	2 K warming	4 x CO_2

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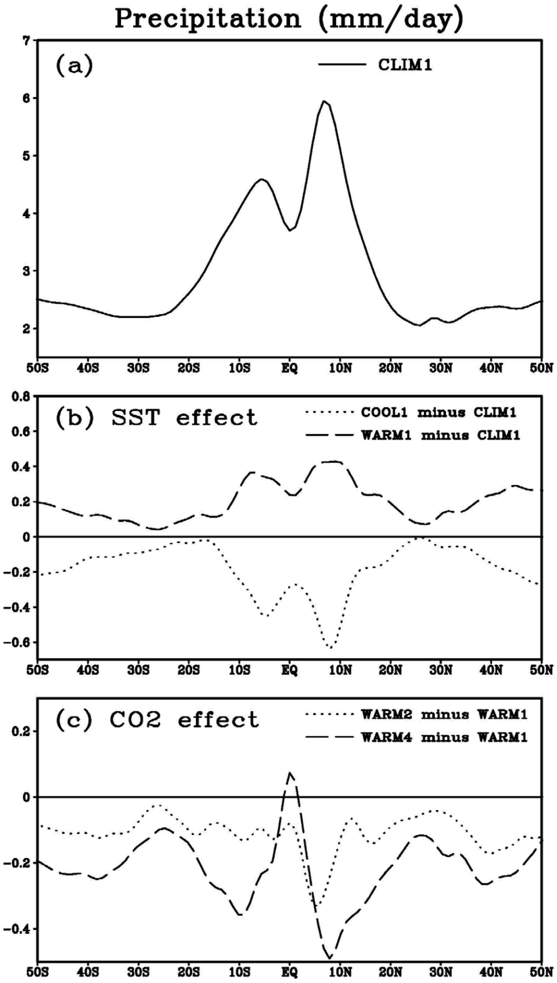

Fig. 1. Zonal-mean precipitation (mm day^{-1}; 10-year averages). (a) CLIM1. (b) The SST effect, shown as differences from CLIM1. (c) The CO$_2$ effect, as differences from WARM1.

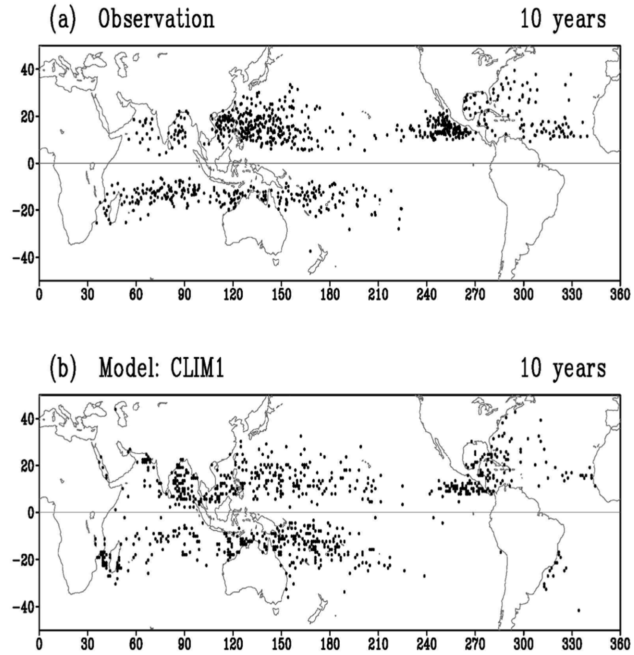

Fig. 2. Geographical distribution of TC genesis. (a) Observed TC positions where maximum surface wind first reached 17.2 ms^{-1} (34 kt) or more, based on 'best track' data (1989–1998) obtained from a website of Unisys Corporation. (b) Initial positions of simulated TCs (CLIM1).

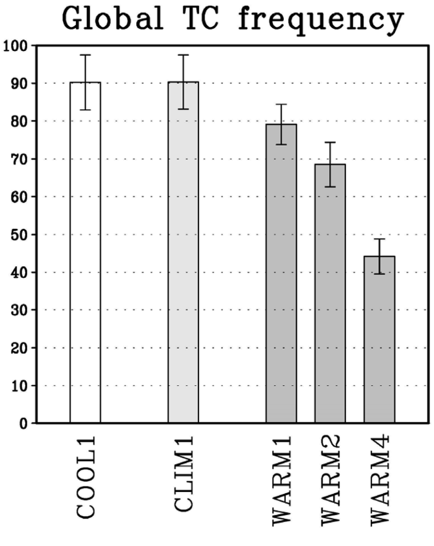

Fig. 3. Global frequencies of TC genesis (annual-mean numbers). The error bars indicate 95% confidence intervals.

numerical experiments. The effect of SST warming (cooling) is substantial intensification (weakening) of precipitation in the tropical and higher latitudes (Fig. 1b).

On the other hand, as the effect of CO$_2$ enhancement, precipitation decreases significantly in most of the tropical and higher latitudes (Fig. 1c). Such weakening of precipitation was also shown by SY2004. Tropospheric temperature and the dry static stability do not change much (SY2004) in the CO$_2$ effect.

4. Changes in tropical cyclone climatology

We performed objective tracking of TCs in the model outputs of 24-hour intervals, following the criteria of a previous study (Sugi et al. 2002). Relative vorticity, wind speed, and warm-core temperature structures are automatically tested under the criteria for selecting TCs.

Initial positions of the simulated TCs are plotted in Fig. 2b for CLIM1. As compared with observational data (in Fig. 2a), a reasonably realistic geographical distribution of TCs is simulated in this experiment.

Figure 3 shows global frequencies of TC genesis in the numerical experiments. TC frequencies of COOL1 and CLIM1 are almost the same, while that of WARM1 is somewhat lower than those of COOL1 and CLIM1. The number of TCs in WARM4 is surprisingly fewer than that of WARM1, which indicate that CO$_2$ enhancement has large impacts on TC frequencies. Statistical significance of the differences in TC frequencies is shown in Table 2. While the SST effect is partly significant at 95% confidence level, the CO$_2$ effect is highly significant (at 99% level for WARM4).

It is curious that both of the SST and CO$_2$ effects seem to be 'nonlinear' in Fig. 3. We have examined this apparent nonlinearity, and the results show that it is not statistically significant for each of the SST and CO$_2$

Table 2. Statistical significance at 95% and 99% confidence levels. The Student's t-test was applied to the differences in global frequencies of TC genesis between the numerical experiments.

	Test of difference	Confidence level 95%	 99%
SST effect	COOL1−CLIM1	No	No
	WARM1−CLIM1	Yes	No
	WARM1−COOL1	Yes	No
CO_2 effect	WARM2−WARM1	Yes	No
	WARM4−WARM2	Yes	Yes
	WARM4−WARM1	Yes	Yes

Table 3. The same as Table 2, but for 'nonlinearity' of the SST and the CO_2 effects upon global frequencies of TC genesis.

	Test of nonlinearity	Confidence level 95%	 99%
SST effect	WARM1+COOL1−2x (CLIM1)	No	No
CO_2 effect	WARM4+WARM1−2x (WARM2)	No	No

effects (Table 3).

Note that the CO_2 radiative forcing of 'WARM2 minus WARM1' is approximately the same as that of 'WARM4 minus WARM2', since the radiative forcing is almost proportional to the logarithm of CO_2 concentration.

Longitudinal and latitudinal distributions of TCs are shown in Fig. 4. The WARM4 curves are significantly lower than the other curves in most of the longitudes and the latitudes, which indicate that the CO_2 effect is not confined to specific regions. On the other hand, the curves of WARM1 are substantially lower than those of COOL1 and CLIM1 only in specific regions: the eastern Pacific and the Atlantic basins (around 120°W−60°W), and the Northern Hemisphere.

In Fig. 5, frequency distribution of TCs is plotted as a function of TC intensity (in terms of the maximum surface wind). It seems that there are no significant shifts in TC intensities between the experiments. Reduction in TC frequency from the CO_2 effect is clear again for the WARM4 curve.

Note that the simulated TCs are much weaker than those in the real atmosphere, as pointed out by Sugi et al. (2002) using the same model. The horizontal resolution of the model seems to be insufficient for realistic simulation of the TC intensity. Recently, Oouchi et al. (2005) have investigated TC climatology using another AGCM with much higher horizontal resolution of a 20-km grid, and reported that intense TCs tend to become even more intense in a global-warming experiment.

5. Discussion and conclusions

The separate effects of SST warming and CO_2 increase on the TC frequency have been investigated in the present paper. The results of the numerical experiments are summarized in Table 4. While the global TC frequency decreases by about 6% on average (relative to CLIM1) for SST increase by 2 K, the global TC frequency decreases by about 22% on average (relative to WARM1) for CO_2 doubling.

As the results of SST warming (and cooling) by 2 K, the global changes in TC frequency are relatively small (in comparison with the CO_2 effects). The SST warming causes a significant increase in climatological precipitation, and this indicates intensification of convective heating (SY2004) and should have some influences to activate tropical circulation in terms of vertical mass flux. But, larger warming in the upper troposphere causes higher static stability, which should have some impacts to weaken the tropical circulation and to decrease TC frequency (Sugi et al. 2002). It seems that these two conflicting factors, in terms of TC frequency, may cancel out to a large extent.

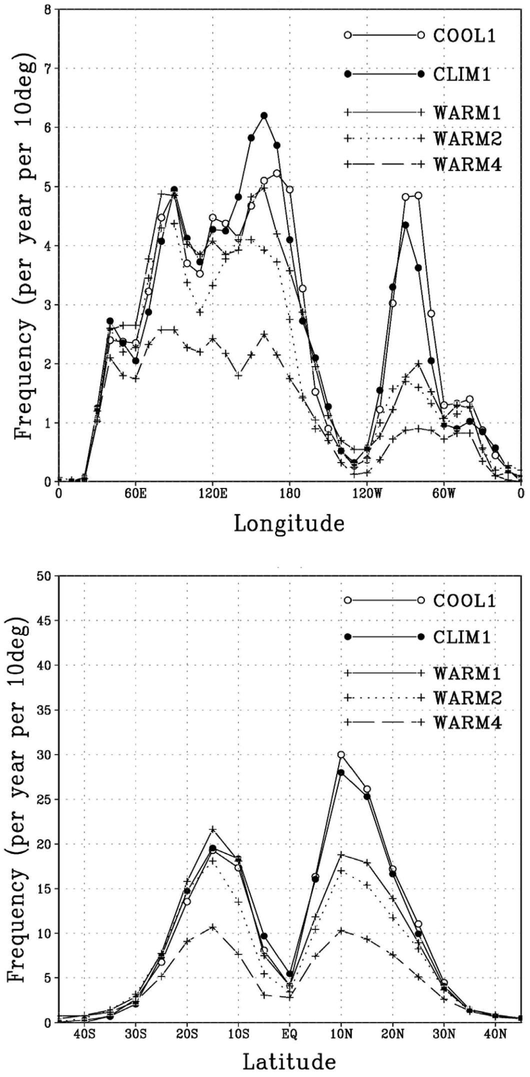

Fig. 4. Longitudinal (top) and latitudinal (bottom) distributions of TC genesis frequencies (annual-mean numbers per 10°). Each TC is counted only once at the initial position. The curves are smoothed.

The increase in CO_2 concentration has large impacts to reduce TC frequency all over the tropics. This can be attributed to the decreased precipitation (as shown in Table 4). Under the CO_2 enhancement, dry static stability does not change much.

The weakening of precipitation due to the CO_2 enhancement can be explained as an influence of reduction in long-wave radiative cooling in the lower troposphere (SY2004). There may be an additional explanation for the decrease in TC frequency as the CO_2 effect in our experiments. While surface air temperature over the ocean is almost fixed to the prescribed SST data, surface temperature over continents may rise

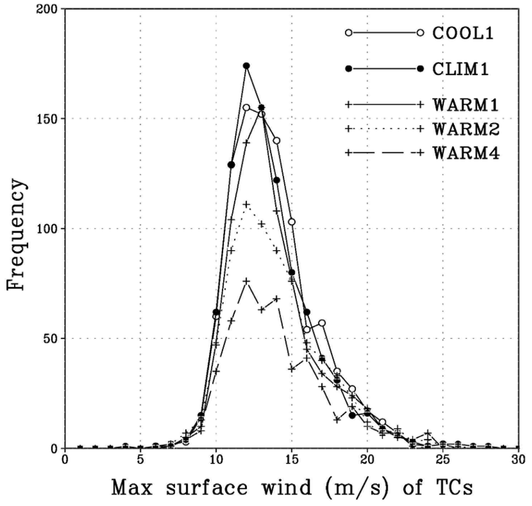

Fig. 5. Frequency distribution of TCs shown as a function of the maximum surface wind speed (annual-mean numbers). The maximum wind data are used at an interval of 24 hours for each TC.

Table 4. Changes in precipitation and dry static stability, averaged between 30°S and 30°N, and changes in global frequencies of TC genesis. Dry static stability is defined as difference in potential temperature between 250 hPa and the surface (SY2004).

[SST effect]	Change (relative to CLIM1)		
	Precipitation	Stability	TC frequency
COOL1	−5.6%	−9.6%	−0.1%
WARM1	+6.1%	+9.4%	−12.4%

[CO_2 effect]	Change (relative to WARM1)		
	Precipitation	Stability	TC frequency
WARM2	−3.0%	+0.2%	−13.4%
WARM4	−6.3%	+0.4%	−44.1%

Table 5. Differences in surface air temperature and precipitation (WARM4 minus WARM1; 10-year-mean values). Averages between 30°S and 30°N for all the grid points (sea+land) and over the sea only and the land only.

	Sea + Land	Sea only	Land only
Surface air temperature (K)	+0.23	+0.08	+0.66
Precipitation (mm/day)	−0.23	−0.33	+0.05

under the high-CO_2 condition. This land-ocean contrast may cause monsoon-like effects, which may lead to increase in precipitation over the land and decrease over the sea, as pointed out by Tokioka and Saito (1992). In Table 5, such changes in surface temperature and precipitation are examined for the case of CO_2 quadrupling. Although precipitation does not change much over the land, precipitation becomes significantly weaker over the sea, which should contribute to the decrease in TC frequency over the ocean, in the CO_2 effect.

In conclusion, the simulated decreases in TC frequency in response to the global warming are largely caused by the CO_2 effect. Thus, the present paper emphasizes that the CO_2 concentration is one of the essential factors for the simulation of future TC climatology, even when SST is given as an external condition.

Although the present study shows a new evidence which suggests relationships between TC frequency and large-scale fields, including precipitation and dry static stability, detailed mechanisms of such connections are not yet clear. Static stabilization in a greenhouse-warmed climate can weaken tropical circulation in terms of vertical mass flux, which may cause overall weakening of tropical disturbances including TCs. But there is other possibility such that intense TCs become more intense, while total TC frequency decreases (Oouchi et al. 2005). Further studies on changes in TC climatology are necessary.

Acknowledgments

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References

Bengtsson, L., M. Botzet and M. Esch, 1996: Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes? *Tellus*, **48A**, 57–73.

Kuo, H. L., 1974: Further studies of the parameterization of the influence of cumulus convection on large-scale flow. *J. Atmos. Sci.*, **31**, 1232–1240.

Lacis, A. A., and J. E. Hansen, 1974: A parameterization for the absorption of solar radiation in the earth's atmosphere. *J. Atmos. Sci.*, **31**, 118–133.

Oouchi, K., J. Yoshimura, H. Yoshimura, R. Mizuta, S. Kusunoki and A. Noda, 2005: Tropical cyclone climatology in a global-warming climate as simulated in a 20-km-mesh global atmospheric model. *J. Meteor. Soc. Japan*, (submitted).

Sugi, M., K. Kuma, K. Tada, K. Tamiya, N. Hasegawa, T. Iwasaki, S. Yamada and T. Kitade, 1990: Description and performance of the JMA operational global spectral model (JMA-GSM88). *Geophys. Mag.*, **43** (3), 105–130.

Sugi, M., A. Noda and N. Sato, 2002: Influence of the global warming on tropical cyclone climatology: An experiment with the JMA Global Model. *J. Meteor. Soc. Japan*, **80**, 249–272.

Sugi, M., and J. Yoshimura, 2004: A mechanism of tropical precipitation change due to CO_2 increase. *J. Climate*, **17**, 238–243.

Tokioka, T., and M. Saito, 1992: Numerical experiments on the characteristics of ocean/continent-scale climate changes in global warming produced by CO_2 increase. *Proc., Workshop on Effects of Global Climate Change on Hydrology and Water Resources at the Catchment Scale*, Tsukuba, Japan, Public Works Research Institute, 57–66.

Yoshimura, J., M. Sugi and A. Noda, 2004: Influence of greenhouse warming on tropical cyclone frequency. *J. Meteor. Soc. Japan*, (submitted).

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