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A Reduction in Global Tropical Cyclone Frequency due to Global Warming

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Abstract

In this report, we present the results from our recent experiments using 20 km-mesh and 60 km-mesh atmospheric general circulation models with prescribed sea surface temperatures (SST). The results of the experiments consistently show a reduction in the global tropical cyclone frequency due to global warming. By the experiments with the models of different resolution and with different SST changes, we find that the reduction in the global tropical cyclone frequency due to global warming is a very robust feature. In contrast, the regional tropical cyclone frequency change varies a lot among the experiments with different SST change distribution. We find that the regional tropical cyclone frequency change is sensitive to relative SST change distribution. This suggests that the regional change is strongly affected by the change in tropical circulation and convective activity which is dominated by relative SST distribution patterns, and therefore, for a reliable projection of the regional change, a reliable projection of the pattern of SST change is vitally important.

1. Introduction

In the Summary for Policy Makers (SPM) of the Intergovernmental Panel on Climate Change (IPCC) (2007), the conclusion regarding the future tropical cyclone frequency change is written as "There is less confidence in projections of a global decrease in numbers of tropical cyclones". This conclusion is based on the discussion in Chapter 10 of the IPCC (2007). In the chapter, the discussion on the global tropical cyclone frequency change is based on six references (Sugi et al. 2002; Yoshimura et al. 2006; McDonald et al. 2005; Bengtsson et al. 2006; Tsutsui 2002; Oouchi et al. 2006). Among these six references, results of the medium resolution (grid size of about 100 km) models (Sugi et al. 2002; Yoshimura et al. 2006; McDonald et al. 2005) and a result of high resolution (20 km mesh) model (Oouchi et al. 2006) consistently indicate a significant decrease in global numbers of tropical cyclones, while results of lower resolution (grid size of 180 km or larger) models (Bengtsson et al. 2006; Tsutsui 2002) show insignificant increase or decrease. In the discussion of IPCC (2007), the medium resolution models are regarded to fall into first category models, which are not able to simulate tropical cyclones reasonably and are not reliable.

Generally speaking, higher resolution models are able to simulate tropical cyclones more realistically, particularly the intense mature stage tropical cyclones, and the results of higher resolution models are considered to be more reliable. Regarding projections of the change in maximum intensity of tropical cyclones, the results from the medium resolution (grid size of about 100 km) models are different from those of high resolution models (grid size of about 20 km), indicating that the medium resolution is not sufficient to reasonably simulate intense tropical cyclones. On the other hand, regarding the projection of the change in global frequency in tropical cyclones, the results of the medium resolution models are consistent with those of higher resolution models, indicating that the medium resolution is sufficient to represent this aspect of tropical cyclones. If we put more reliability on the medium resolution models, we would have more confidence than the IPCC conclusion.

After the IPCC (2007), some studies using higher resolution models appeared (Bengtsson et al. 2007; Gualdi et al. 2008). These studies support the IPCC conclusion, a reduction in the global tropical cyclone frequency, and give some more confidence for the conclusion. In the present report, based on our recent experiments, we show further evidence for the robustness of the reduction of global tropical cyclone frequency due to global warming.

2. Model and experiments

The model used in the experiments is the Japan Meteorological Agency/Meteorological Research Institute global atmospheric model (JMA/MRI AGCM), the same model as used in Oouchi et al. (2006). We conducted eight experiments as shown in Table 1. For the experiments A0–A3, high resolution (20 km-mesh) version is used, while for the experiments B1–B4, medium resolution (60 km-mesh) version is used. Each experiment consists of a pair of integrations: control run for the present day climate simulation and global warming run for the future climate simulation. Integration period of the control run and global warming run are the end of 20th century and the end of 21st century, respectively. The length of integration period of each experiment is shown in Table 1.

Except for the experiments A0, A1 and A2, the sea surface temperature (SST) used for the control runs are the observed SST (HadISST, Rayner et al. 2003). For the control runs of the experiments A0 and A2, climatological SST (with annual variation but without interannual variation; the same as in Oouchi et al. 2006) is used. For the global warming runs, except for the experiment A1, SST change projected by various climate models (atmosphere-ocean coupled models) as indicated in Table 1 is added to the respective SST of the control runs. The SST change is the difference between the time-averaged coupled model SST during the integration period of control run and global warming run of each experiment. In addition, for the experiments A3

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Table 1. The changes in tropical cyclone frequency as projected by 20 km-mesh and 60 km-mesh global atmospheric model experiments. The changes are shown in terms of the ratio of future frequency to present frequency. Statistically significant increase (decrease) at 95% confidence level by two-sided t-test is indicated by red (blue) color. Experiment "O" indicates the experiment by Oouchi et al. (2006)
The models used for the SST change estimation are:
[MRI-CGCM2.3]: Meteorological Research Institute (Japan) coupled model Ver. 2.3.
[MIROC-H]: High Resolution version of Coupled Model by Center for Climate System Research (CCSR), National Institute for Environmental Studies (NIES) and Frontier Research Center for Global Change (FRCGC) (Japan).
[CMIP3]: Ensemble Average of 18 models out of 23 models in Coupled Model Inter-comparison Project 3.
[CSIRO]: Coupled Model of Commonwealth Scientific and Industrial Research Organization (Australia).

Experiments	Resolution	ΔSST	Integration	Ratio(%) of TC frequency Future/Present								
				Global	NH	SH	N Indian	NW Pacific	NE Pacific	N Atlantic	S Indian	S Pacific
O	TL959, 20 km	MRI-CGCM2.3	10 yr	70	72	68	48	62	66	134	72	57
A0	TL959, 20 km	MRI-CGCM2.3	20 yr	71	69	73	61	64	61	122	72	78
A1	TL959, 20 km	MRI-CGCM2.3	20 yr	75	75	75	71	71	70	123	75	73
A2	TL959, 20 km	MIROC-H	10 yr	73	85	58	132	128	50	82	76	10
A3	TL959, 20 km	CMIP3	25 yr	80	79	81	85	74	75	105	95	58
B1	TL319, 60 km	MRI-CGCM2.3	25 yr	80	79	83	88	66	69	158	78	92
B2	TL319, 60 km	MIROC-H	25 yr	94	100	84	179	164	58	106	110	31
B3	TL319, 60 km	CMIP3	25 yr	79	81	75	133	86	67	104	82	64
B4	TL319, 60 km	CSIRO	25 yr	78	71	89	93	113	51	63	78	110

and B1–B4, the difference in the SST trend during the period of control run and global warming run is also added. Note that the SST changes have seasonal variation but no interannual variation. The interannual variations including decadal variations (except for the trend in A3 and B1–B4 experiment) are the same for the control run and corresponding global warming run. Therefore, the difference between the control run and the corresponding global warming run can be regarded as a signal of global warming. One exception is the experiment A1. For the control run and the global warming run of the experiment A1, monthly SST data from the Meteorological Research Institute coupled model (MRI-CGCM2.3) runs are simply used. For these runs the interannual variations of SST are not the same.

The atmospheric concentrations of greenhouse gas and aerosols are taken from the values of the integration period in the A1B scenario for the experiments A0–A2. On the other hand, in the experiments A3 and B1–B4, the aerosols used for the global warming runs are the same as used for the control runs. Three-dimensional distributions of the aerosols used in these experiments are derived from a global chemical transport model (Tanaka et al. 2003). There is some inconsistency in the specification of greenhouse gas and aerosols in these future runs. However, this inconsistency expected to influence only little in our experiments, because the model atmosphere is mainly forced by the prescribed SST in our experiments.

The detection method of simulated tropical cyclones is the same as Oouchi et al. (2006), although some adjustment of the threshold values is made for the 60 km-mesh model experiments, so that the total global number of simulated tropical cyclones in a control run is close to the observed number of tropical cyclones. In the detection criteria, the threshold values for surface pressure drop, maximum wind speed at 850 hPa and average warm core temperature anomaly are 2.0 hPa (1.5 hPa), 15 m s^{-1} (12 m s^{-1}) and 2.0 K (1.5 K), respectively for 20 km- (60 km-) mesh model. The definition of the ocean basin in Table 1 is almost the same as in Oouchi et al. (2006), although a little more realistic boundary between the North Eastern Pacific and the North Atlantic is employed for the experiments A3 and B1–B4 (see Fig. S2 in Supplement 3).

3. Results

3.1 Evaluation of control runs

The control runs for the experiments A0 and A2, which use climatological SST without interannual variation, are basically the same as that of Oouchi et al. (2006). On the other hand, control runs for the experiments A3 and B1–B4 use observed SST (HadISST) with interannual variation. The tropical cyclone counts of each run and observation are summarized in Table S 1 (Supplement 1). We note some systematic biases in the tropical cyclone counts in individual ocean basin. For example, the simulated tropical cyclone counts in Western North Pacific are considerably less than the observation in all runs as in Oouchi et al. (2006). These systematic biases indicate a deficiency of the model, probably in the convection scheme, and need to be improved in the future. Also shown in Table S1 (Supplement 1) are the correlations between the tropical cyclone counts in each ocean basin in the control runs with observed SST (A3P and BP) and the corresponding observed counts. We find that there are significant correlations in Western North Pacific, North Atlantic and Southern Indian Ocean, but no significant correlations in other ocean basins. This suggests that the model captures the tropical cyclone counts variations associated with at least some of the SST variation such as ENSO.

Seasonal variations of the tropical cyclone frequencies in each ocean basin in the two control runs using 20 km-mesh model and 60 km-mesh model with observed SST (A3P and BP) are compared with corresponding observation in Fig. S1 (Supplement 2). Generally, both the 20 km-mesh and 60 km-mesh models reproduce the seasonal variation reasonably well. One exception is the Eastern North Pacific, where both the models produce too many tropical cyclones during the months from

October to January. The observed and the simulated tropical cyclone tracks in the two control runs (A3P and BP) are shown in Fig. S2 (Supplement 3). The simulated tracks are generally in good agreement with the observed tracks, although the simulated tracks tend to be shorter than observation, particularly in the 60 km-mesh model. In summary, although there are some deficiencies in the simulation, the temporal and spatial variations of tropical cyclone frequencies are generally well reproduced by the model. It may be said that overall performance of the model is good enough to assess the changes in tropical cyclone frequencies due to global warming.

3.2 Changes in frequency of tropical cyclones due to global warming

The changes in frequency of simulated tropical cyclones in the eight experiments (A0−A3 and B1−B4) and the experiment by Oouchi et al. 2006 (indicated by "O") are shown in Table 1. The changes are shown by the ratio of the frequency of the global warming run to that of control run. Statistically significant increase (decrease) by t-test at 95% confidence level is indicated by red (blue) color. First, we note that the global frequency of tropical cyclones consistently shows significant decrease, except for the experiment B2. Reduction in the hemispheric frequency is also significant in most experiments. In contrast, the basin-wise frequency changes are considerably different among the experiments with different SST changes. Except for the North Eastern Pacific, where all the experiments show significant decrease, tropical cyclone frequency in each ocean basin shows either significant increase and/or decrease, or insignificant changes, indicating that we can hardly say any conclusion with confidence regarding the projection of basin-wise frequency changes based on these experiments.

Note that the experiment A0 is basically the same as the experiment O (Oouchi et al. 2006) and only difference is the length of integration. Even with this minor difference, we see some notable differences in the magnitude of frequency changes between the two experiments, indicating that there is a statistical uncertainty in the magnitude of the changes in these experiments. The integration period of 10 years in Oouchi et al. 2006 may be too short. We also note that the increase in North Atlantic and decrease in South Pacific are significant in the experiment O, but they are not statistically significant in the experiment A0, although the length of the integration of the latter is longer.

The time-mean SST changes between the control and global warming runs are the same (as of MRI-CGCM 2.3) for both of A0 and A1. The difference between the experiments A0 and A1 is that the climatological SST without interannual variation is used for the A0 control run, while coupled-model SST with interannual variation is used for A1. Therefore, the SST change for the experiment A0 has no interannual variation, while the SST change for experiment A1 has interannual variation. However, the frequency changes of tropical cyclones in the two experiments are similar to each other, although the average annual number of simulated tropical cyclones in the experiment A1 (90.7) is larger than that in the experiment A0 (77.8). The three experiments O, A0 and A1, which have the same time-averaged SST change (MRI-CGCM2.3), show very similar tropical cyclone frequency changes.

The experiments A1−A3 are the 20 km-mesh model experiments with different SST changes used for global warming runs. Similarly, the experiments B1−B4 are the 60 km-mesh model experiments with different SST changes. Note that the names of experiments with the same number indicate that the same SST changes are used in these experiments. For example, both the experiments A1 and B1 use the SST change projected by MRI-CGCM2.3. We note that the models with the same SST changes but different resolution tend to show the similar tropical cyclone frequency changes.

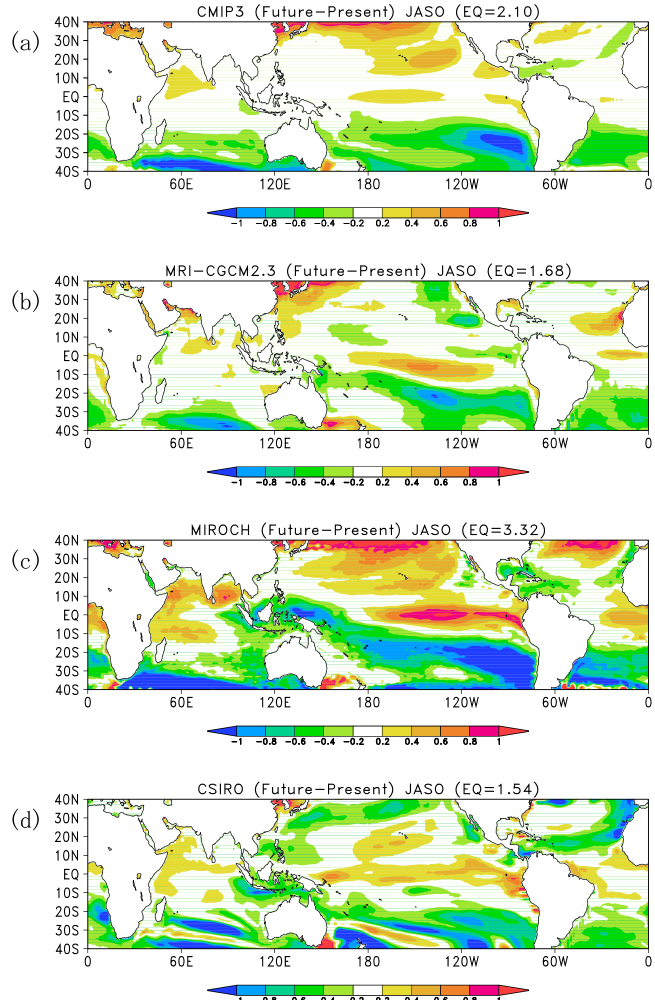

Fig. 1. The SST change for July-October season used in the experiments. The distribution of relative SST change is shown in each panel by subtracting the tropical (20N−20S) average SST increase (indicated at the top of each panel) from the projected SST change. (a) Ensemble average of CMIP3 models, (b) MRI-CGCM2.3 model, (c) MIROC-H model, (d) CSIRO model.

Here, it is important to note that convective activity changes, and therefore, tropical cyclone activity changes appear to be controlled by the distribution of relative SST changes (effect of remote SST) rather than the changes in absolute value of local SST (Sugi et al. 2002; Vecchi and Soden 2007). To see the effect of remote SST clearly, the distribution of relative SST changes (absolute SST changes minus average SST changes in the tropics) projected by different models used in the experiments are shown in Fig. 1. Note that the SST increase is positive everywhere in the tropics, but relative SST change is negative in the region where the SST increase is less than the tropical average. We can see the regional changes in the tropical cyclone frequency appear to be closely related to the relative SST changes. The increase in the North Atlantic tropical cyclone frequency in the experiments O and B1 is consistent with a positive relative SST change over the

North Atlantic in MRI-CGCM2.3 (Fig. 1b). On the other hand, the decrease in the North Atlantic tropical cyclone frequency in the experiment B4 is consistent with a negative relative SST change over the North Atlantic in CSIRO model (Fig. 1d).

We note increases in tropical cyclone frequency in the North Western Pacific and North Indian Ocean in the experiments A2 and B2, for which the MIROC-H SST change is used. The increase in frequency in the North Indian Ocean is consistent with the positive relative SST change over the North Indian Ocean in MIROC-H model. Note that the most tropical cyclone genesis in the North Indian Ocean takes place in the months of May, June, and from October to December (Fig. S1, Supplement 2). During these months the MIROC-H SST change over the Indian Ocean is relatively large (Fig. S3, Supplement 4). On the other hand, the explanation of the increase in frequency of tropical cyclone in the Western North Pacific may not be so straightforward, as the relative SST increase in MIROC-H model is not so largely positive there. We speculate that an effect of the negative relative SST change over the Equatorial Western Pacific may be responsible for the increase in tropical cyclone frequency in the North Western Pacific. We need further study to understand the mechanism of tropical cyclone frequency change in all ocean basins.

In Fig. 1, we note a north-south contrast in the relative SST changes. Positive changes dominate in the Northern Hemisphere, while negative changes dominate in the Southern Hemisphere. This north-south contrast is most significant in the MIROC-H SST change. Note that this north-south contrast in the relative SST change can be seen throughout the year (Fig. S3 in Supplement 4). The most significant contrast in the MIROC-H SST is consistent with the relatively larger decrease in the Southern Hemisphere tropical cyclone frequency compared with the decrease in the Northern Hemisphere in the experiments A2 and B2.

4. Concluding remarks

In this report, we have shown that the reduction in the global tropical cyclone frequency due to global warming is a very robust feature. In contrast, the regional tropical cyclone frequency change varies a lot among the experiments with different SST changes, indicating that the regional tropical cyclone frequency change is sensitive to SST change distribution. The sensitivity of the regional tropical cyclone frequency change to SST change distribution patterns suggests that a reliable projection of the pattern of SST change is vitally important for a reliable projection of the regional changes.

It is important to note that the projected future SST changes, estimated from individual coupled climate models and used to force the atmospheric models in our study, may include not only the SST changes due to the A1B climate forcing, but also the SST differences associated with multi-decadal internal variability in the models, particularly if only a few decades are used for averaging, as was done in our study. If the response of TCs to the internal variability signal is comparable to or larger than the response to the climate forcing signal, then differences among our simulations in TC frequency changes may in fact be largely reflecting simulated internal variability, rather than actual model differences in response to A1B forcing. This caveat particularly applies to the individual model results (i.e., other than the CMIP3 ensemble results in Table 1). In that regard, the individual model TC change results in Table 1, especially for the individual basins such as the Atlantic, should be interpreted with great caution.

In this report, we focused on the tropical cyclone frequency change in our recent experiments with medium and high resolution models. Other aspects of tropical cyclone activity changes in these experiments, such as changes in intensity and precipitation, will be reported on in separate papers.

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Supplements

1. Table S1: TC frequency in each ocean basin.
2. Figure S1: Seasonal variation of TC frequency.
3. Figure S2: TC tracks.
4. Figure S3: Relative SST changes.

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