Mechanism of the Indian Ocean Tropical Cyclone Frequency Changes due to Global Warming

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1. Introduction

Recent high resolution models consistently show that the global tropical cyclone (TC) frequency will decrease in the future due to global warming (Knutson et al., 2010). Sugi et al. (2002) pointed out that the reduction of global TC frequency in the future is closely related to the weakening of upward mass flux in the tropics. Recently, Sugi and Yoshimura (2012) found a clear decreasing trend of global TC frequency throughout the 228-year simulation for the period 1872-2099, which is also closely related to a decreasing trend of upward mass flux.

In contrast to the global TC frequency change, there is a very large uncertainty in the projected regional TC frequency changes (Knutson et al., 2010). Sugi et al. (2009) showed that one of the major sources of uncertainty in the projection of regional TC frequency changes is the uncertainty of projected pattern of sea surface temperature (SST) changes. In addition, it is possible that the mechanism of TC frequency change could be different in each region. In the present study, we further explore the possible mechanism of global and regional TC frequency changes due to global warming based on a series of experiments with a high resolution MRI-AGCM, with particular focus on the TC frequency changes in the Indian Ocean.

2. Hypothesis

Based on the previous studies (Yoshimura and Sugi, 2005; Held and Zhao, 2011; Sugi et al., 2012), we can propose the following hypothesis as a

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mechanism of the global and regional TC frequency changes due to global warming (Table 1). We consider two effects: CO_2 effect and SST effect. In the CO_2 effect, the overlap of CO_2 and water vapour long wave absorption bands is playing an important role (Sugi and Yoshimura, 2004). The atmospheric cooling will decrease due to the overlap effect when CO_2 is increased, leading to a reduction of precipitation, upward mass flux and global TC frequency. On the other hand, in the SST effect a static stability change is playing an important role. When SST is increased, atmospheric temperature and moisture will increase, leading to an increase in precipitation. However, since the increase in dry static stability is larger than the increase in precipitation, the upward mass flux in the tropics will decrease, leading to a decrease in global TC frequency.

3. Model and Experiment

In order to further explore the mechanism of global and regional TC frequency changes due to global warming, five 25-year experiments have been conducted using the 60 km-resolution MRI-AGCM3.2 (Mizuta et al., 2012) as shown in Fig. 1. For the present climate run (P run), observed sea surface temperature (SST) and atmospheric concentration of greenhouse gases (GHG) including CO_2 and aerosols are prescribed. For the future climate run (F run), the CMIP3 ensemble mean SST anomaly is added to the present observed SST and GHG and aerosols at the end of 21st century of A1B scenario is prescribed. For the future SST run (SSTF run), future SST and present GHG are prescribed, while for the future CO_2 run (CO_2F run), future GHG and present SST are prescribed. In addition, for the uniform SSTA run (USSTA run), future GHG is used as in CO_2F run but uniform 1.83K (global mean of CMIP mean SSTA) is added to the present observed SST.

The difference between CO_2F run and P run (CO_2F-P) or F run and SSTF run (F-SSTF) indicates the CO_2 effect, while the difference between SSTF run and P run (SSTF-P) or F run and CO_2F run (F-CO_2F) indicates the SST effect.

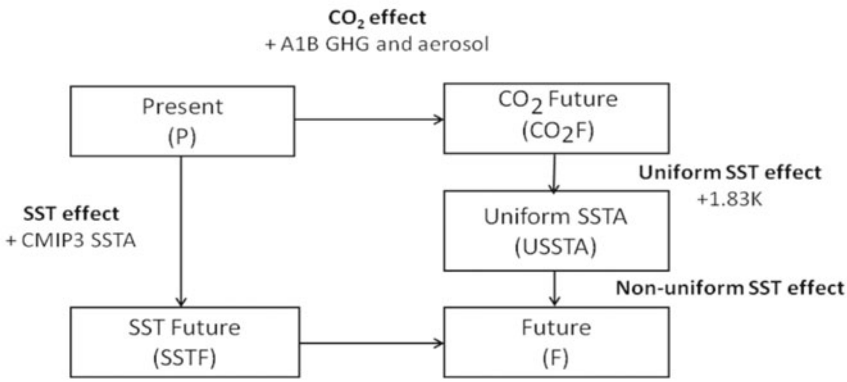


Fig. 1: Experiments.

Table 1: Hypothesis for the mechanism of global and regional TC frequency changes

Effect		*Global change*					*Regional change*
		Radiative cooling	*Precipitation*	*Stability*	*Upward massflux*	*TC frequency*	*(TC frequency)*
CO_2	CO_2	Decrease	Decrease		Decrease	Decrease	
	GHG	Increase	Increase		Increase	Increase	
SST	Uniform SSTA	Increase	Increase	Increase	Decrease	Decrease	
	Non-uniform SSTA						Shift

On the other hand, the difference between USSTA run and CO_2F run indicates the uniform SST effect, while the difference between F run and USSTA run indicates the non-uniform SST effect.

4. Global TC Frequency Changes

Main results of this study are reported in Sugi et al. (2012). The global TC frequency changes are summarized in Fig. 2. The global TC frequency in F run is 24% less than that of P run. The CO_2 effect evaluated by the difference between CO_2F run and P run (F run and SSTF run) is 5.6% (9.8%) reduction of TC frequency, while SST effect evaluated by the difference between F run and CO_2F run (SSTF run and P run) is 19.3% (15.6%) reduction. These results are basically consistent with previous studies (Yoshimura and Sugi, 2005; Held and Zhao, 2011), although the CO_2 effect is relatively less than the previous studies probably due to the effect of other GHGs included in the present study. Figure 2 indicates that the uniform SSTA effect is a significant reduction of global TC frequency (18.7% reduction), while the non-uniform SSTA effect does not change the global TC frequency.

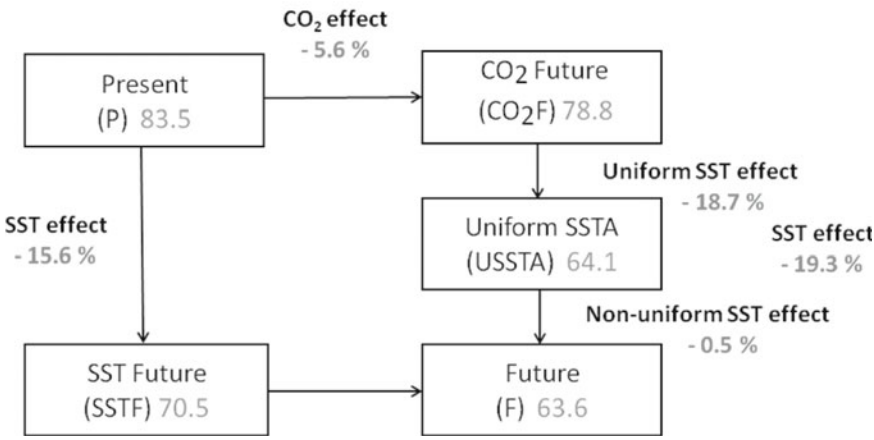


Fig. 2: TC frequency changes.

5. Regional TC Frequency Changes

The regional TC frequency changes are summarized in Fig. 3. The CO_2 effect, SST effect and total effect (CO_2 effect + SST effect) on regional TC frequencies are shown in Figs 3a, 3b and 3c, respectively. Figure 3c indicates that the total effect is an overall reduction of TC frequency in most regions. However, in Fig. 3c we can see a significant increase of TC frequency in central North Pacific and western part of the South Indian Ocean. These TC frequency increases are mainly due to the SST effect as shown in Fig. 3b. In Fig. 3a, we can see a significant TC frequency increase due to CO_2 effect in north-western

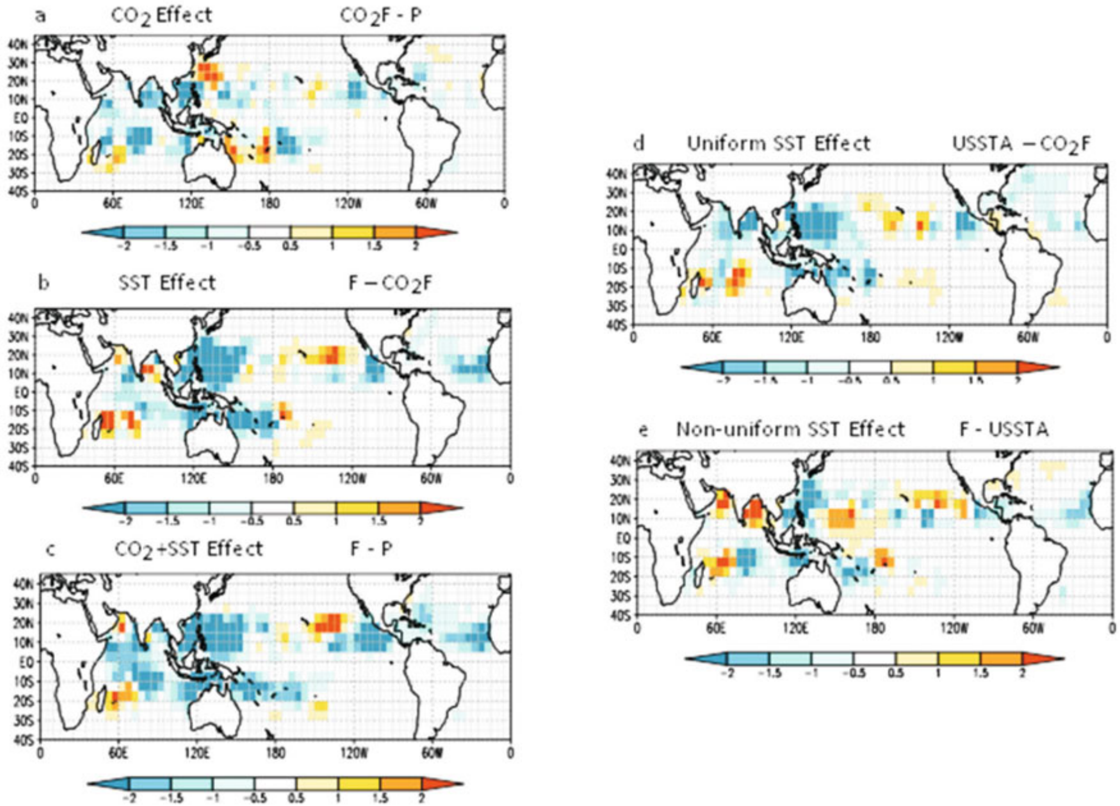


Fig. 3: CO_2 effect and SST effect on annual mean TC frequency. (a) CO_2 effect, (b) SST effect, (c) total (CO_2+SST) effect, (d) uniform-SST effect, (e) non-uniform SST effect.

part of the west North Pacific Ocean, but this TC frequency increase is not seen in Fig. 3c because of a larger TC frequency decrease due to SST effect as shown in Fig. 3b.

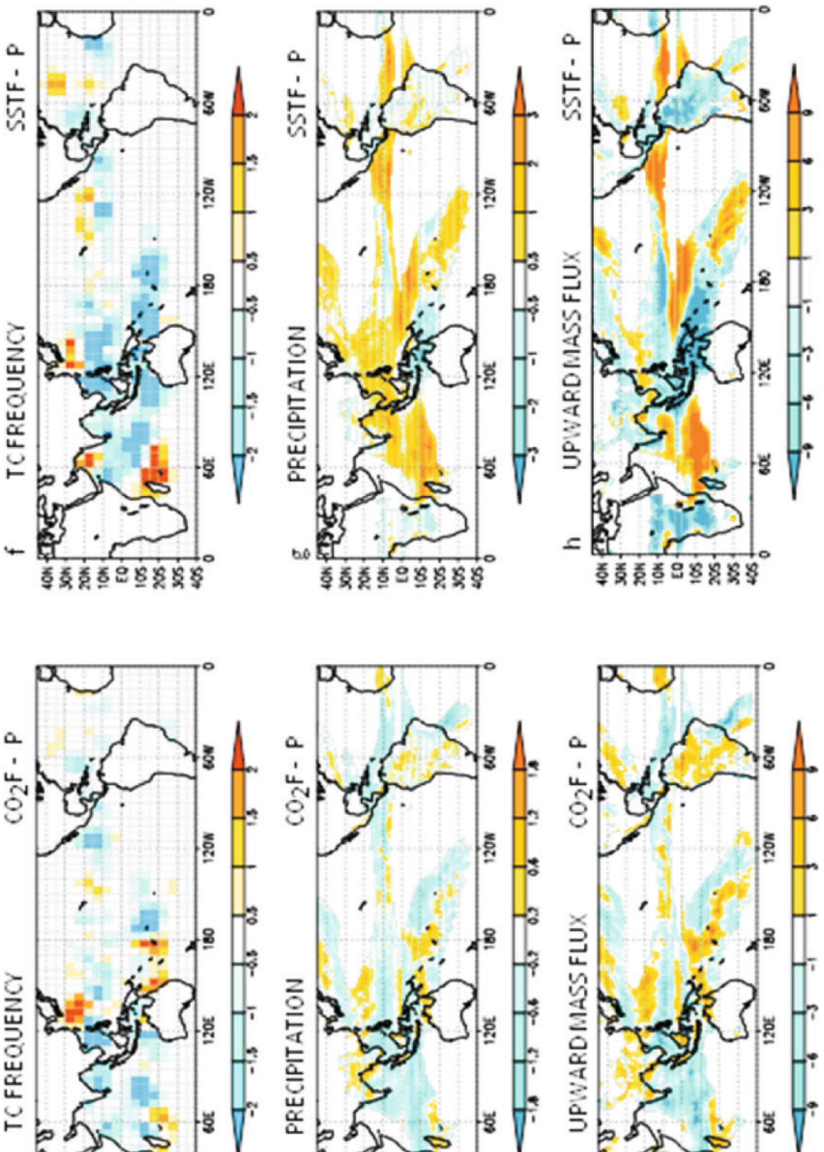
The SST effect (Fig. 3b) is further divided into uniform SST effect (Fig. 3d) and non-uniform SST effect (Fig. 3e). The uniform SST effect is an overall reduction of TC frequency with some regions of TC frequency increase, while the non-uniform SST effect is a mixture of the regions of TC frequency increase and decrease. The non-uniform SST effect does not change the global TC frequency, but it causes a shift of active deep convection area and significantly affects the regional TC frequencies.

Figure 4 shows the CO_2 effect and SST effect on TC frequency, precipitation, upward mass flux, vertical wind shear and saturation deficit. The effect of CO_2 increase is to decrease precipitation, upward mass flux and TC frequency. On the other hand, the effect of SST increase is to increase precipitation but to decrease upward mass flux and TC frequency. Despite the opposite sign of the changes in precipitation, both CO_2 effect and SST effect decrease upward mass flux and reduce TC frequency. We note, however, in some regions the SST effect on upward mass flux do not agree well with that on TC frequency. Such disagreement may be explained to some extent by the changes in vertical wind shear or saturation deficit due to the SST effect as shown in Figs 4i and 4j. For example, TC frequency decreases in the eastern North Pacific and the Atlantic, although precipitation increases over the same regions. The decrease of TC frequency in these regions may be explained by the increase of vertical wind shear as shown in Fig. 4i.

6. Indian Ocean TC Frequency Changes

Figure 3c shows an overall reduction of TC frequency in the most part of the Indian Ocean due to the CO_2 effect and SST effect. We note, however, significant increases in TC frequency in the western-north part of the Arabian Sea and the western-south part of the South Indian Ocean mainly due to the SSTA effect as shown in Fig. 3c. There is a significant TC frequency increase in the Bay of Bengal due to the SST effect (Fig. 3b), but this TC frequency increase is not seen in Fig. 3c because of a large TC frequency decrease due to CO_2 effect shown in Fig. 3a. It should be noted that the TC frequency increase in the Arabian Sea and the Bay of Bengal in Fig. 3b is mainly due to the non-uniform SST effect shown in Fig.3e. The uniform SST effect is to reduce the TC frequency in both the Arabian Sea and the Bay of Bengal as shown in Fig. 3d.

The overall reduction of TC frequency in most part of the Indian Ocean corresponds to the reduction of precipitation and upward mass flux due to the CO_2 effect as shown in Figs 4b and 4c. On the other hand, the TC frequency increase in the western part of the South Indian Ocean may be explained by the increase of precipitation and upward mass flux due to the SST effect as shown in Figs 4g and 4h. We note that similar explanation is not applicable to the TC


a
TC FREQUENCY
CO2F - P
b
PRECIPITATION
CO2F - P
c
UPWARD MASS FLUX
CO2F - P
f
TC FREQUENCY
SSTF - P
g
PRECIPITATION
SSTF - P
h
UPWARD MASS FLUX
SSTF - P

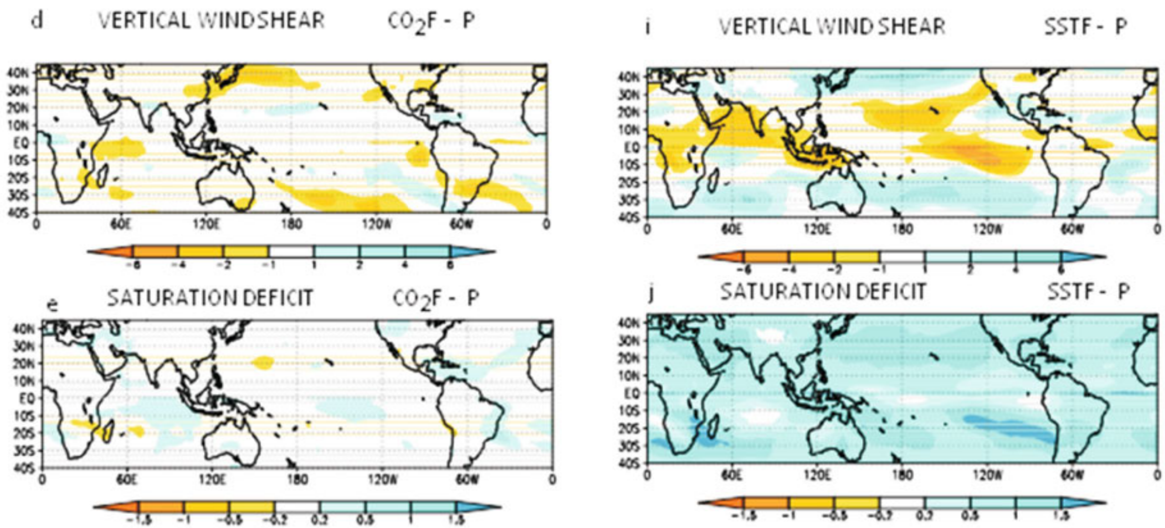


Fig. 4: CO_2 effect and SST effect on annual mean TC frequency (a, f), precipitation (b, g), upward mass flux (p-velocity at 500 hPa) (c, h), vertical wind shear between 200 hPa and 850 hPa (d, i), and saturation deficit at 600 hPa (e, j). Each variable is averaged over TC season of respective hemisphere (NH: Jun-Nov, SH: Jan-Apr).

frequency increase in the Arabian Sea, because there is very little change in precipitation and upward mass flux in the region. However, we can see a significant decrease in vertical wind shear in the Arabian Sea, which probably explain the TC frequency increase.

7. Discussion

We have noted that the CO_2 effect is 5.6% reduction of global TC frequency when evaluated by the difference between CO_2F run and P run, while it is 9.8% reduction when evaluated by the difference between F run and SSTF run (Fig. 2). This may suggest that the CO_2 effect is larger for the warmer climate. However, other possibility is that this is only a result of statistical uncertainty, because the TC frequency estimated by a single 25-year run is subjected to a large statistical uncertainty. The problem of statistical uncertainty is even more serious for the regional TC frequency changes. In this study we estimated the TC frequency change based on a pair of single 25-year run. Ideally, an ensemble experiment with large number of members should be conducted for a reliable estimate of regional TC frequency changes. Recently, Murakami et al. (2012a) conducted such an ensemble experiment using the MRI-AGCM3.2. They showed the overall TC frequency reduction with increases in central North Pacific, Arabian Sea and western South Indian Ocean, which is basically consistent with the present study.

In the present study, we analyzed the TC frequency in the Northern Hemisphere (NH) and Southern Hemisphere (SH) separately during the respective TC season (June to November for NH; January to April for SH). However, we should note that TC seasons of the North Indian Ocean are pre-monsoon period (May and June) and post-monsoon period (October to December). Furthermore, a recent study by Murakami et al. (2012b) revealed that there is a marked seasonality in the TC frequency change in the North Indian Ocean. They showed that TC frequency will decrease in pre-monsoon season but increase during monsoon season both in the Arabian sea and the Bay of Bengal, while it will increase in the Arabian Sea but decrease in the Bay of Bengal in the post-monsoon season. As a result, the annual mean TC frequency will increase in the Arabian Sea but decrease in the Bay of Bengal. This annual mean TC frequency changes are consistent with the present study.

8. Conclusions

Global TC frequency is projected to decrease by about 24% by the end of 21st century. Both CO_2 effect and uniform SSTA effect cause a reduction of upward mass flux, leading to the reduction of global TC frequency. In the Indian Ocean, in addition to an overall decrease in TC frequency, increases in TC frequencies are projected in the western-north part of the Arabian Sea and in the western-south part of the South Indian Ocean. These increases of TC frequency are mainly due to the non-uniform SSTA effect. The decreased vertical wind shear seems to be responsible for the increase in TC frequency in the Arabian Sea, while the increased upward mass flux associated with the enhanced precipitation is responsible for the increase in TC frequency in the South Indian Ocean.

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