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Key Points:
- The 4K-cooler climate experiment is conducted using a high-resolution AGCM
- Number of TCs is significantly increased in the 4K-cooler climate
- Tropical cyclone genesis can occur at SST well below 26°C

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More tropical cyclones in a cooler climate?

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Abstract Recent review papers reported that many high-resolution global climate models consistently projected a reduction of global tropical cyclone (TC) frequency in a future warmer climate, although the mechanism of the reduction is not yet fully understood. Here we present a result of 4K-cooler climate experiment. The global TC frequency significantly increases in the 4K-cooler climate compared to the present climate. This is consistent with a significant decrease in TC frequency in the 4K-warmer climate. For the mechanism of TC frequency reduction in a warmer climate, upward mass flux hypothesis and saturation deficit hypothesis have been proposed. The result of the 4K-cooler climate experiment is consistent with these two hypotheses. One very interesting point is that the experiment has clearly shown that TC genesis is possible at sea surface temperature (SST) well below 26°C which has been considered as the lowest SST limit for TC genesis.

1. Introduction

Studies in the mid-1990s to early 2000s first revealed a possibility of reduction of global tropical cyclone (TC) frequency in a warmer climate by numerical experiments using medium horizontal resolution (grid size of about 100 km) atmospheric global climate models (AGCMs) [*Bengtsson et al*., 1996; *Sugi et al*., 2002]. In the mid-2000s, Meteorological Research Institute/Japan Meteorological Agency (MRI/JMA) group conducted experiments using a 20 km resolution JMA/MRI-AGCM [*Oouchi et al*., 2006]. The model was run on the Earth Simulator, which was more than 100 times faster than the supercomputers at that time. The experiments clearly revealed a reduction of global TC frequency, as well as an increase of the number of intense TCs. The experiments using the Earth Simulator stimulated the research activity using high-resolution (grid size of about 50 km or less) AGCMs in the world. The MRI group also conducted a number of experiments using 20 km and 60 km resolution MRI-AGCMs with different sea surface temperatures (SSTs) and different cumulus parameterization schemes [*Murakami et al*., 2012a, 2012b]. Based on the many studies in the world, including the MRI group's extensive works, recent review reports concluded that a reduction of global tropical cyclone frequency, as well as an overall intensification of tropical cyclones, is likely in the future warmer climate [*Knutson et al*., 2010; *Christensen et al*., 2013].

Recently, however, two studies have shown very different results. One model experiment with MRI-AGCM showed a clear decreasing trend of global TC frequency during 20th century and 21st century [*Sugi and Yoshimura*, 2012], while in contrast another experiment, which is a downscaling experiment from low-resolution coupled model experiments, showed a clear increasing trend of global TC frequency from mid-20th century to the end of 21st century [*Emanuel*, 2013]. The result of the former one is consistent with most previous studies using AGCMs, while the latter one is opposite to them. This indicates that not all the researchers are convinced of the reduction of global TC frequency in a warmer climate, although the reduction was shown by many AGCM experiments.

2. Hypotheses

One of the reasons why researchers are not convinced of the reduction of global TC frequency in a warmer climate is that the mechanism of the TC frequency change is not fully understood yet. We do not have a good theory for TC frequency change such as the maximum potential intensity theory for TC intensity change [*Emanuel*, 1986; *Holland*, 1997]. Two hypotheses, upward mass flux hypothesis and saturation deficit hypothesis, were proposed so far for the TC frequency change [*Knutson et al*., 2010; *Christensen et al*., 2013]. In the upward mass flux hypothesis, the reduction of global TC frequency is linked to the reduction of upward mass flux at midtroposphere in the tropics [*Sugi et al*., 2002; *Held and Zhao*, 2011; *Sugi et al*., 2012]. The reduction of the upward mass flux is a very robust result in all climate model experiments for future warmer climate

[*Vecchi and Soden*, 2007; *Held and Soden*, 2006]. The reduction of upward mass flux is considered to be a result of increased atmospheric stability [*Sugi et al*., 2002, 2012]. In a warmer climate, both atmospheric moisture and precipitation increases. The rate of precipitation increase is constrained by the rate of radiative cooling increase which is much less than the rate of moisture increase [*Allen and Ingram*, 2002]. As a result, the rate of precipitation increase is much less than the rate of stability increase that is close to the rate of moisture increase. The rate of increase in upward mass flux associated with convective precipitation, which is the rate of precipitation increase minus the rate of stability increase, is negative. Thus, the upward mass flux decreases in a warmer climate.

It should be noted that in a climate system in radiative-convective equilibrium, temperature lapse rate is close to that of moist adiabat. As the temperature lapse rate of moist adiabat decreases with increasing atmospheric moisture, the stability increases in a warmer climate with more moisture; and therefore, the reduction of upward mass flux is physically reasonable, although some observational studies suggest that the models tend to overestimate the stability increase during the last few decades [*Santer et al*., 2008; *Fu et al*., 2011]. In contrast, we do not have so far a physically reasonable explanation for the link between the reduction of upward mass flux and the reduction of global TC frequency, although it is demonstrated by many model experiments. It is important to note here that the upward mass flux hypothesis can explain a reduction of TC frequency in $2 \times CO_2$ experiments, in which atmospheric CO_2 concentration is doubled but SST is not changed. It was shown that in $2 \times CO_2$ experiments atmospheric temperature and water vapor changed only a little but precipitation, upward mass flux, and TC frequency significantly decreased [*Sugi and Yoshimura*, 2004; *Yoshimura and Sugi*, 2005; *Held and Zhao*, 2011; *Sugi et al*., 2012].

On the other hand, in the saturation deficit hypothesis, the reduction of TC frequency in a warmer climate is linked to the increase of saturation deficit, which is a difference between saturated specific humidity and actual specific humidity, at lower troposphere [*Emanuel et al*., 2008; *Emanuel*, 2010]. They argue that the dependence of TC activity on water vapor should not be on relative humidity but saturation deficit and developed a new genesis potential index based on saturation deficit instead of relative humidity [*Emanuel*, 2010]. An idealized experiment revealed that larger saturation deficit leads to slower development of a weak vortex and less chance for tropical cyclone genesis [*Rappin et al*., 2010]. Larger saturation deficit leads to entrainment of drier air into upward mass flux of convection and less net heating (convective heating minus adiabatic cooling). Thus, the increased saturation deficit in a warmer climate may result in a reduction of upward mass flux, indicating that the saturation deficit hypothesis may not be independent of upward mass flux hypothesis. However, there is one important difference between the two hypotheses. The saturation deficit hypothesis cannot explain a reduction of TC frequency in the $2 \times CO_2$ experiments, in which saturation deficit changes very little but precipitation, upward mass flux, and TC frequency significantly decrease [*Sugi and Yoshimura*, 2004; *Yoshimura and Sugi*, 2005; *Held and Zhao*, 2011; *Sugi et al*., 2012].

3. Method

The 4K-cooler climate experiment is a standard experiment using a high-resolution atmospheric global climate model. First, the 25 year present climate experiment was conducted using the 60 km resolution MRI-AGCM3.2 with observed SST for the period 1979–2003 as a lower boundary condition for the atmospheric model [*Murakami et al*., 2012b]. For the 4K-cooler (warmer) climate experiment, the SST was uniformly decreased (increased) by 4K globally. The atmospheric concentration of greenhouse gases and aerosols for the experiment was the same as the present climate experiment. It should be noted that by this experimental design we do not intend to duplicate anthropogenic global warming (cooling) but elucidate the mechanism of TC activity change associated with a climate change.

The TC detection threshold values in the TC tracking algorithm was adjusted to the 60 km resolution model, so that the number of simulated TCs (vortices with tropical storm intensity) in the present climate experiment becomes close to the observed number [*Murakami et al*., 2012b].

4. Results

Here we present the results of 4K-cooler climate experiment. The results are compared with present climate experiment and 4K-warmer climate experiment. Figure 1 shows annual mean global TC frequency in the three

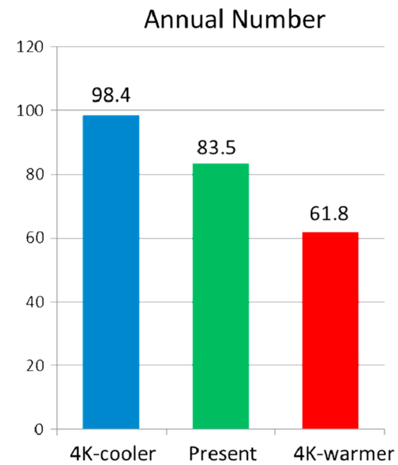

Figure 1. Mean annual global TC numbers in 4K-cooler (warmer) and present climate experiments.

experiments. Significantly, more number of TCs are simulated in the 4K-cooler climate experiment compared with the present climate experiment, while a fewer number of TCs are simulated in the 4K-warmer climate experiment. The result of more number of TCs in the cooler climate is not surprising. It is rather expected result, because many experiments so far have shown the reduction of global TC frequency in a warmer climate. One important point here is that our new experiments have shown that the temperature-TC frequency relationship is valid in a very large temperature change ranging from −4K to +4K.

We also note that the above two hypotheses are also valid for the wide temperature range as well. Table 1 shows tropical mean stability, precipitation, upward mass flux, saturation deficit, and global TC frequency and mean TC intensity in the three experiments. In the 4K-cooler climate experiment, precipitation decreases but stability decreases at larger rate, leading to increases in upward mass flux and TC frequency compared to the present climate experiment. These changes are just opposite to the changes in the 4K-warmer climate experiment and consistent with the upward mass flux hypothesis. In the 4K-cooler climate experiment, saturation deficit decreases and TC frequency increases. This is consistent with the saturation deficit hypothesis. Table 1 shows that the mean life time maximum TC intensity decreases in the 4K-cooler climate experiment. This is also consistent with the conclusion of many previous studies that the mean TC intensity increases in a warm climate.

In Figure 2, relationship between TC genesis location and seasonal mean SST are shown for the three experiments. Figures 2a–2c are for July-August-September, which is the Northern Hemisphere main TC season, while Figures 2d–2f is for January-February-March, which is the Southern Hemisphere main TC season. We can see that the TC genesis locations in the three experiments are more or less similar to each other. In the present climate experiment, most TCs form over the ocean with SST higher than 28°C and some TCs form with SST between 26°C and 28°C (Figures 2b and 2e). In the 4K-cooler climate experiment, most TCs form over the ocean with SST higher than 24°C and some TCs form with SST between 22°C and 24°C (Figures 2a and 2d), while in the 4K-warmer climate experiment, most TCs form over the ocean with SST higher than 32°C and some TCs form with SST between 30°C and 32°C (Figures 2c and 2f). Figure 2 shows that the area of TC genesis in 4K-cooler (warmer) climate does not shrink (expand) compared with the present climate. This result is consistent with the finding by *Hoyos and Webster* [2012]. They found based on Coupled Model Intercomparison Project phase 3 projections that the area of dynamic warm pool, where the deep convection is active and atmospheric heating is positive, remains constant during the period 1950–2100, although the threshold (area boundary) SST increases from 26.6°C to 28.5°C.

Table 1. Annual Mean TC Frequency, Lifetime Maximum TC Intensity, and TC-Related Tropical Mean (30°N–30°S) Environmental Quantities for 4K-Cooler (Warmer) and Present Climate Experiments[a]

	4K-Cooler	Present	4K-Warmer
N: Annual TC frequency	98.4 (+18%)	83.5	61.8 (−26%)
I: Life time max intensity (m/s)	21.9 (−6%)	23.2	26.7 (+15%)
S: Stability (K)	37.0 (−16%)	44.1	53.3 (+21%)
P: Precipitation (mm/d)	3.07 (−12%)	3.50	4.00 (+14%)
ω: Upward mass flux (hPa/h)	1.81 (+12%)	1.61	1.45 (−10%)
χ: Saturation deficit (g/kg)	3.01 (−31%)	4.35	6.33 (+46%)

[a]S: stability (difference in potential temperature at 200 hPa and 200 hPa) (K), P: precipitation (mm/d), ω: upward mass flux (hPa/h), χ: saturation deficit (g/kg). All the changes between 4K-cooler (warmer) climate and present climate experiments are highly statistically significant (p values < 0.001).

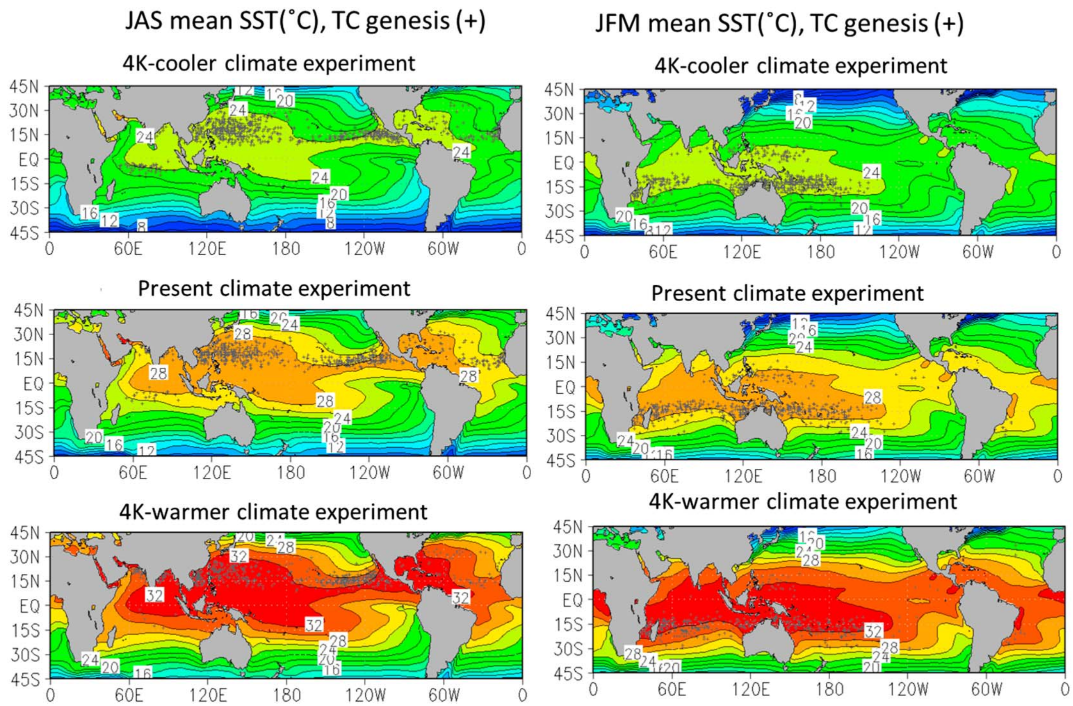

Figure 2. Seasonal mean SST (°C) and TC genesis location (+mark) in 25 years of 4K-cooler, present, and 4K-warmer climate experiments. (left) July-August-September mean. (right) January-February-March mean.

Figure 3 shows annual mean frequency distributions of SST at the time and location of TC genesis for the three experiments. Green, blue, and red curves indicate the SST distribution for present, 4K-cooler, and 4K-warmer climate experiments, respectively. Note that the simulated TC genesis SST distribution in the present climate experiment is almost identical to the observed SST distribution shown by green dashed curve. The TC genesis SST ranges are 20–27°C, 23–31°C, and 28–35°C, with peak TC genesis frequency at around 25.5°C, 28.5°C, and 32.5°C, for the 4K-cooler, present, and 4K-warmer climate experiments, respectively. It is interesting to note that most TC genesis occurs with SST well below 26°C in the 4K-cooler climate, although the SST of 26°C has been considered as the lowest limit for TC genesis [*Gray*, 1975; *Anthes*, 1982]. Figure 3 suggests that the lower limit of SST for TC genesis is an indication of the lowest boundary of the relatively warm SST region, where tropical convection is active, and subject to change with changing climate. The absolute value of 26°C is not a physically critical value but happens to be the indication of the relatively warm region for the present climate.

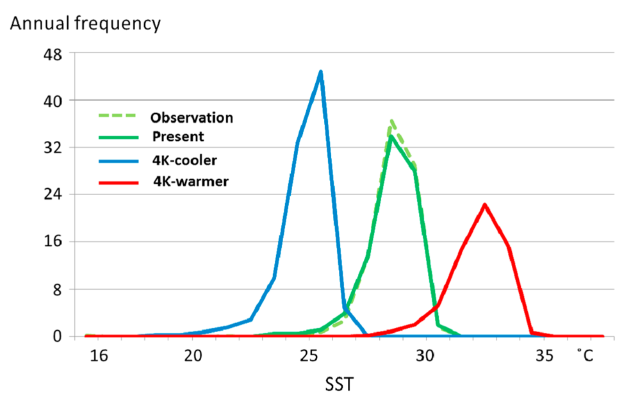

Figure 3. Annual SST frequency distribution at the time and location of TC genesis for observation (green dashed), 4K-cooler climate (blue solid), present climate (green solid), and 4K-warmer climate (red solid).

Although the 4K-cooler climate experiment has clearly shown that TC genesis is possible at SST well below 26°C, this is a result of one model experiment and may not be robust. We should note that TC activity simulated by climate models considerably depends on model formulation, particularly deep convection schemes [*Reed and Jablonowski*, 2011; *Murakami et al.*, 2012a, 2012b; *Zhao et al.*, 2013].

5. Discussion

Based on the results of our experiments, we can conclude that we would have more tropical cyclones in a cooler climate, and tropical cyclone genesis can occur with sea surface temperature well below 26°C. Although the robustness of these conclusions is yet to be examined by other models, they may further raise many interesting questions. In even much cooler climate, for example, 10K-cooler climate, do we have even more TCs? Can TCs form with SST below 10°C? Is there a lowest SST limit for TC genesis? Did we have more TCs in the ice age? There are some studies to answer these questions. For example, there are a few studies on the tropical storms in last glacier maximum [*Hobgood and Cerveny*, 1988; *Merlis*, 2014]. We know that there are polar lows over the Arctic Ocean, some of which has a structure like hurricane and called arctic hurricane [*Emanuel and Rottuno*, 1989; *Businger and Baik*, 1991], suggesting that TCs can form with very low SST. We also know that the climate system is basically in the radiative-convective equilibrium, suggesting that well-organized convection systems like TCs may be a necessary component of a climate system. Above mentioned questions are interesting scientific questions. Answering to these questions would contribute to further understand mechanism of the changes in tropical cyclones in changing climate.

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