In: Cyclones: Formation, Triggers and Control
Editors: K. Oouchi and H. Fudeyasu
ISBN: 978-1-61942-976-5
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Chapter 5

REDUCTION OF GLOBAL TROPICAL CYCLONE FREQUENCY DUE TO GLOBAL WARMING

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ABSTRACT

In this chapter, we review recent medium and high resolution GCM studies on the changes in tropical cyclone (TC) frequency due to global warming, and present a coherent explanation for the mechanism of projected changes, with a main focus on the reduction of global TC frequency. The reduction of global TC frequency is explained by a weakening of tropical circulation, which is closely related to a large increase in atmospheric stability and a small increase in precipitation. An interesting point is that the overlap effect of CO_2 and water vapor absorption bands in long wave radiation is playing an important role in the small increase in precipitation.

INTRODUCTION

In the Summary for Policy Makers (SPM) of the Intergovernmental Panel for Climate Change Fourth Assessment Report (IPCC AR4) [1], it is concluded that: "Based on a range of models, it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperature (SST). There is less confidence in projections of a global decrease in numbers of tropical cyclones." This conclusion is based on the chapter ten of the IPCC AR4 [1], in which the discussion is based on the results of many coarse resolution (grid size of 100km or more) GCMs, one high resolution (grid size of 20km) GCM and several high resolution (grid size of 30km or less) regional models. The discussion overlooked that recent medium resolution (about 100km resolution) GCM results consistently

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indicated a global decrease in global numbers of TCs in the future. After the IPCC AR4 [1], a number of high resolution models consistently showed a reduction of TC frequency due to global warming [2]. However, it has been noted that there are large uncertainties in regional TC frequency changes projected by various models, although the models consistently show a reduction of global TC frequency [2]. In this regard, we believe that the projections for the global change and regional change in the TC frequency should be considered separately, the former being more reliable than the latter. Moreover, a background behind the IPCC's conclusion that the projection of the TC frequency is less reliable than that of the TC intensity may be that the reduction of TC frequency is an unexpected projection. As a natural guess, we tend to think that we will have more intense TCs and more number of TCs in a warmer climate with increased moisture, because the energy source of TCs is the atmospheric moisture. For an unexpected projection to be accepted, a reasonable physical explanation is required. In this regard, understanding the mechanism of the reduction of global TC frequency in the future warmer climate is very important. The objective of this chapter is to review the GCM studies on the changes in TC frequency and intensity due to global warming, and present a coherent explanation for the mechanism of the projected changes, with a main focus on the change in the global TC frequency.

TC Frequency Changes Projected by GCMs

Results from medium and high resolution GCM experiments before the IPCC AR4 on the TC frequency changes are summarized in Table 1 [3-6]. The GCM experiments consistently show a reduction of global TC frequency, while there is substantial disagreement in the regional TC frequency changes (in Table 1, the regional changes are shown for North Western Pacific and North Atlantic). It should be noted that the physical processes of the JM8911 model and the Japan Meteorological Agency (JMA)/ Meteorological Research Institute (MRI) model are quite different, and the four models in Table 1 are independent each other. Although the resolution of the JMA/MRI model used by Oouchi et al. [6] is much higher than the other three models, the results of the four models are similar regarding the global TC frequency change. After the IPCC AR4, a number of medium and high resolution model projection experiments have been conducted [7-10], and summarized in Knutson et al. [2]. These medium and high resolution model projection experiments consistently also show a reduction of global TC frequency and substantial disagreement in the regional TC frequency changes.

Table 1. TC frequency changes as simulated by medium and high resolution GCMs. Changes are shown by the ratio of future TC frequency to present TC frequency

Reference	Model	Resolution	Experiment	Global	NWP	NA
Bengtsson et al. [3]	ECHAM4	120 km	5 years× 2	63 %	66 %	87 %
Sugi et al. [4]	JMA8911	120 km	10 years× 2	66 %	34 %	161 %
McDonald et al. [5]	HadAM3	100 km	15 years × 2	94 %	79 %	75 %
Oouchi et al. [6]	JMA/MRI	20 km	10 years × 2	70 %	62 %	134 %

Bengttson et al. [3] first showed that a significant reduction in the global TC frequency is likely in the future warm climate based on their GCM experiment (Table 1). They suggested that the reduction of global TC frequency is related to the changes in global scale fields such as Hadley circulation and subtropical jets. Sugi et al. [4] also found a significant reduction in the global TC frequency in their experiment (Table 1). They also suggested that the reduction in global TC frequency is closely related to a weakening of the tropical circulation. They further suggested that the weakening of the tropical circulation is explained by a large increase in the atmospheric dry stability and small increase in the tropical precipitation in the GCM experiment.

WEAKENING OF TROPICAL CIRCULATION

Held and Soden [11] and Vecchi and Soden [12] showed that a weakening of tropical circulation, a weakening of the upward mass flux associated with tropical convections, is a very robust feature in the climate change projected by Third Coupled Model Intercomparison Project (CMIP3) models. They attributed the weakening of upward mass flux to a small increase in precipitation and a large increase in moisture. The weakening of tropical circulation with small increase in precipitation indicates a weakening of hydrological cycle in terms of mass flux and a little intensification of hydrological cycle in terms of moisture flux. To understand the mechanism of the weakening of tropical circulation, Sugi et al. [4] considered a basic energy balance in the tropical circulation. The approximate energy balance equation in the tropics is expressed as,

$$\omega \frac{\partial \theta}{\partial p} \approx \frac{\theta}{T} \frac{Q}{C_p} \tag{1}$$

In the equation, θ is potential temperature, ω is vertical p-velocity, p is pressure, T is temperature, Q is diabatic heating and C_p is specific heat of dry air at constant pressure.

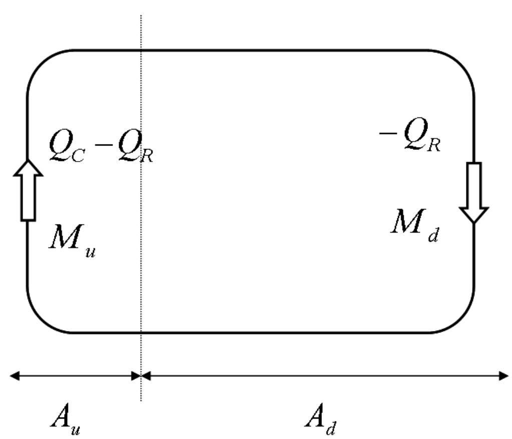


Figure 1. A schematic diagram showing the energy balance of tropical circulation.

As shown schematically in Figure 1, the basic tropical circulation consists of intense upward motions associated with convective updrafts in very small areas A_u and weak downward motions (compensating subsidence) in very large areas A_d, and upper level and lower level flows connecting these upward motions and downward motions. In the upward motion areas, the diabatic heating Q_C-Q_R (condensation heating in the convective clouds minus radiative cooling) is balanced by the adiabatic cooling associated with the upward motion, while in the downward motion areas, the radiative cooling Q_R is balanced by the adiabatic warming associated with the downward motion. Total upward mass flux $M_u=A_u \times \omega_u$ and downward mass flux $M_d=A_d \times \omega_d$ in the tropics should balance, neglecting the small net transport of mass between the tropics and mid-latitudes. Furthermore, the total diabatic heating in the upward motion areas in the tropics should be balanced by the total radiative cooling in the downward motion areas. Therefore, using the Eq.(1) and dry static stability S defined as,

$$S \equiv \frac{C_p T}{\theta} \left| \frac{\partial \theta}{\partial p} \right| \quad (2)$$

the energy balance at the mid-tropospheric level (e.g. 500hPa) for the upward motion area and downward motion area can be expressed as,

$$M_u S \approx (Q_C - Q_R) A_u \quad (3)$$

and

$$M_d S \approx Q_R A_d \quad (4)$$

The Eqs. (3) and (4) indicate that if the diabatic heating is increased and the stability does not change, then the upward and downward mass fluxes should increase. However, if the stability significantly increases and its increase is larger than the increase in diabatic heating, then the mass flux should decrease. Therefore, the weakening of tropical circulation can be explained by the significant increase in stability and little increase in precipitation (diabtic heating). The next question is why stability significantly increases, while precipitation increases only little in the global warming.

The reason for why the stability increases significantly is that the stability is closely related to the atmospheric moisture. We should note that the lapse rate of temperature in the tropics is close to the moist adiabat lapse rate, because the temperature profile in deep convective clouds is close to moist adiabat. The temperatures of deep convective clouds at level of free convection (LFC) near the cloud base and level of neutral buoyancy (LNB) near the cloud top are the same as the respective environment atmospheric temperatures. Therefore, if we define the mean tropospheric stability in the tropics as the difference in potential temperature at LNB and LFC, then it is the same as the potential temperature difference between LNB and LFC of a moist adiabat. This potential temperature difference $\Delta\theta=\theta_{LNB} - \theta_{LFC}$ is proportional to the condensation heating of the saturated air parcel rising from LFC to LNB along a moist adiabat:

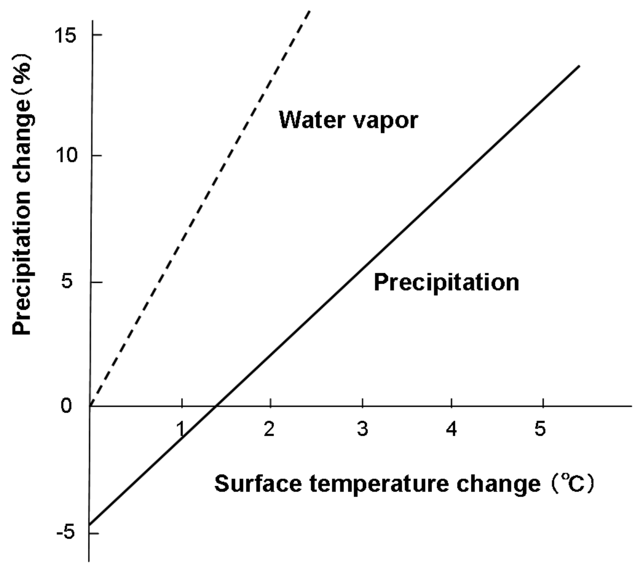
$$\Delta\theta = \theta_{LNB} - \theta_{LFC} \approx \frac{L}{C_p} q_{LFC} \left(\frac{p_0}{p} \right)^{\frac{R}{C_p}} \qquad (5)$$

where L is latent heat of condensation and R is gas constant for dry air. The potential temperature difference $\Delta\theta$ is nearly proportional to the atmospheric moisture near the cloud base. This is the reason for why stability of the tropical atmosphere is closely related to the atmospheric moisture and it significantly increases due to global warming.

PRECIPITATION CHANGE

The next question is why precipitation does not increase much, when the atmospheric moisture significantly increases due to global warming. To this question Allen and Ingram [13] answered as "changes in the overall intensity of the hydrological cycle are controlled not by the availability of moisture, but by the atmospheric energy". Figure 2 shows the relations between the changes in precipitation and atmospheric moisture and the change in surface temperature when CO_2 is doubled. The precipitation increases by about 3% as surface temperature increases 1°C, while atmospheric moisture increases about 7%. This is because the change in the precipitation is controlled by the change in radiative cooling in the atmosphere which is much less than the change in the moisture. It should be noted that this is consistent with the energy balance shown in the Figure 1. The total condensation heating in the upward motion areas is in balance with the total radiative cooling in the downward motion areas.

Another important point in Figure 2 is that the line showing the precipitation-temperature relation does not pass through the origin of the graph and there is a large negative intercept. This means that if the surface temperature does not increase at all when CO_2 is doubled, then the precipitation decreases as much as 5%. This precipitation decrease in response to CO_2 doubling can be explained by the reduction of radiative cooling due to the overlap effect of long wave radiation of CO_2 and water vapor long wave absorption bands [14]. Since CO_2 and water vapor have absorption bands of long wave radiation in the same wave length (overlap of absorption bands), the downward long wave flux emitted from CO_2 in the upper atmosphere is absorbed by the water vapor in the lower troposphere, and the radiative cooling there due to water vapor is significantly reduced (overlap effect). In general, when greenhouse gas in the atmosphere is increased, it increases downward long wave flux and increases atmospheric radiative cooling as well as heating of the earth's surface (greenhouse effect). On the other hand, when CO_2 is increased, the radiative cooling at the lower troposphere is significantly reduced by the overlap effect. Figure 2 indicate that the overlap effect is playing a significant role in the precipitation change due to CO_2 increase. However, in Figure 2 the overlap effect may be overestimated. Yoshimura and Sugi [15] and Andrews et al. [16] have shown that precipitation decreases by about 2 to 3% due to the overlap effect when CO_2 is increased without changing SST.



This figure is made based on the Figure 2 in Allen and Ingram [13].

Figure 2. Precipitation change (solid line) and water vapor change (dashed line) as a function of surface temperature change when CO2 is doubled.

Mechanism of the Reduction of Global TC Frequency

We can summarize the mechanism of the reduction of global TC frequency as follows. The atmospheric moisture significantly increases due to global warming. This moisture increase leads to a large increase in the atmospheric stability, while precipitation (condensation heating) and radiative cooling do not increase as much. As a result, tropical circulation becomes weaker. The upward branch of the tropical circulation is the upward mass flux associated with convective updraft. The weakening of tropical circulation indicates a decrease in upward mass flux as a whole. And this decrease in the upward mass flux associated with convective updraft leads to the reduction of global TC frequency as simulated in the GCMs.

The last point in the above argument, the relationship between the decrease in total upward mass flux in the tropics and the decrease in the global TC frequency may not be straightforward. The mass flux associated with TCs is only a few percent of total mass flux in the tropics, because the precipitation associated with TCs is only a few percent of total precipitation in the tropics. It is not yet clear how a change in total tropical mass flux can constrain the number of TCs.

However, the above argument well explains the results of GCM experiments so far conducted. In particular, the experiments which examined separately the effects of SST increase and CO_2 increase on the TC frequency strongly support the above argument. In the experiment by Yoshimura and Sugi [15], TC frequency is reduced by 12% when SST is uniformly increased by 2K with fixed CO_2, although TC frequency does not change much when SST is uniformly decreased by 2K. On the other hand, global TC frequency decreases by 13% when CO_2 is doubled with fixed SST. Recently Held and Zhao [17] conducted a similar experiment. They found that the reduction of global TC frequency when CO_2 is doubled with fixed SST is about 10%, which is almost the same as the reduction of global TC frequency when SST is increased by 2K with fixed CO_2. These experiments indicate that both in the CO_2 increase experiment and SST increase experiment, the rate of reduction of global TC frequency is similar. They showed that the rate of reduction of the upward mass flux in the both experiments is also similar. It should be noted, however, that the reason for the reduction of the mass flux is different in the two experiments. The reason is a reduction of precipitation due to the overlap effect in the CO_2 increase experiment, while it is an increase in stability in the SST increase experiment, in which precipitation increases. An important point is that whatever the reason is, the reduction of mass flux leads to a reduction of TC frequency in both the CO_2 increase experiments and SST increase experiments. On the other hand, an increase in saturation-deficit, which was proposed by Emanuel et al. [18] as a mechanism for the TC frequency reduction, cannot explain the reduction of TC frequency in the CO2 increase experiment, in which SST is fixed and saturation deficit does not change.

REGIONAL TC FREQUENCY CHANGE

Table 1 shows significant disagreement among the GCM experiments in the changes in the regional TC frequency, in contrast to the overall agreement in the global TC frequency change. The disagreement among the GCM experiments in the projected regional TC frequency is also found in recent medium and high resolution GCM experiment [2]. To explain this disagreement, we need to consider some other factors, which might affect the regional TC frequency, in addition to the argument discussed above with regard to the global TC frequency change. Sugi et al. [4] noted that the regional TC frequency change in their experiment is closely related to the pattern of the SST change. A significant decrease in the typhoons in the North Western Pacific and considerable increase in the Hurricanes in the North Atlantic are related to the relatively small increase and large increase in SST in the respective regions. A significant increase in the number of TC in the central Pacific in the McDonald et al. [5] seem to be related to a relatively large increase in SST over the region in their experiment. Recently, Sugi et al. [10] conducted a series of experiments with high resolution models, in which different SST changes projected by different climate models are prescribed. They found that the regional TC frequency changes projected by different models are similar to each other if the same SST change distributions are prescribed. The regional TC genesis frequency is closely related to the regional convective activity, and therefore, the changes in regional TC frequency are sensitive to relative SST change distribution which dominates the changes in regional convective activities. Thus, the difference among the models in regional TC frequency projection may be explained to a large extent by the difference among the distributions of SST change used in each experiment. The regional frequency of TCs clearly depends on the relative SST distribution.

Increase of Intense TC Frequency

Some high resolution models clearly show that the number of intense TCs may increase, even though the number of relatively weak TCs may decrease due to global warming [6, 7, 9, 19]. The increase in the number of intense TCs is consistent with regional model experiments by Knutson et al. [20] and Walsh et al. [21], while the decrease in the number of relatively weak TCs is consistent with the reduction in global total TC frequency. This suggests that these two changes are compatible and do not contradict with each other. Even though the total upward mass flux in the tropics decreases and the number of tropical cyclogenesis is reduced, once a TC forms, the TC may develops into a very intense storm by TC intensification mechanism which is not much affected by the general weakening of the tropical circulation.

Summary and Discussion

We have reviewed possible mechanisms of the changes in frequency and intensity of TCs as simulated by GCMs, with a focus on the change in global TC frequency. The reduction of global TC frequency is explained by a weakening of tropical circulation, that is, a reduction of total tropical mass flux associated with the convective updrafts. The reduction of total mass flux in the tropics is closely related to a large increase in the atmospheric stability caused by the significant increase in the atmospheric moisture due to global warming and a small increase in the precipitation (condensation heating) which drives the tropical circulations. A very interesting point is that the overlap effect of CO_2 and water vapor is playing an important role in the little increase in precipitation.

The mechanism of the TC frequency change due to global warming often discussed by using Yearly Genesis Parameter (YGP) by Gray [22] or Genesis Potential Index (GPI) by Emanuel and Nolan [23]. Sugi et al. [4] examined the changes in YGP parameter in their GCM experiment, and found that the dynamical factors such as vertical wind shear and low level relative vorticity play more important roles to determine the regional TC frequency than the thermo-dynamical factors such as SST and moist stability. In other words, a change in SST distribution can cause a change in tropical circulation and indirectly affect the tropical cyclogenesis in a remote region, rather than directly affect through a change in the thermo-dynamical structure over the region of the SST change. McDonald et al. [5] also noted the importance of dynamical factors in the changes in regional TC frequency. Yokoi and Takayabu [24] discussed the mechanism of changes in regional TC genesis frequency in western North Pacific by using GPI. Murakami et al. [25, 26] discuss the changes in regional TC genesis in North Atlantic and western North Pacific by using a modified GPI. These discussions on the mechanism of the future TC frequency changes using YGP or GPI must be viewed with caution. YGP or GPI is an empirical formula developed on the present day climate condition, and its applicability in the future climate condition is not guaranteed. Moreover, the several factors included in these formula are not independent each other, being most of them related to conditions favorable for development of deep convections.

The changes in TC frequency is no doubt related to the changes in the activity of deep convections in the tropics. The main point of our argument is that in the global warming the activity of deep convection is enhanced in terms of precipitation but it is reduced in terms of upward mass flux, and the latter leads to the reduction of global TC frequency. From dynamical perspective, the reduced upward mass flux leads to a reduced low level vorticity convergence, which in turn leads to less TC genesis. On the other hand, from thermo-dynamical perspective, the enhanced precipitation associated with convections and reduced upward mass flux are favorable for development of TC warm core, which in turn leads to more intense TCs.

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